Results from the SDSS-II Supernova Survey

Rick Kessler
University of Chicago

ANL Seminar Dec 9, 2008

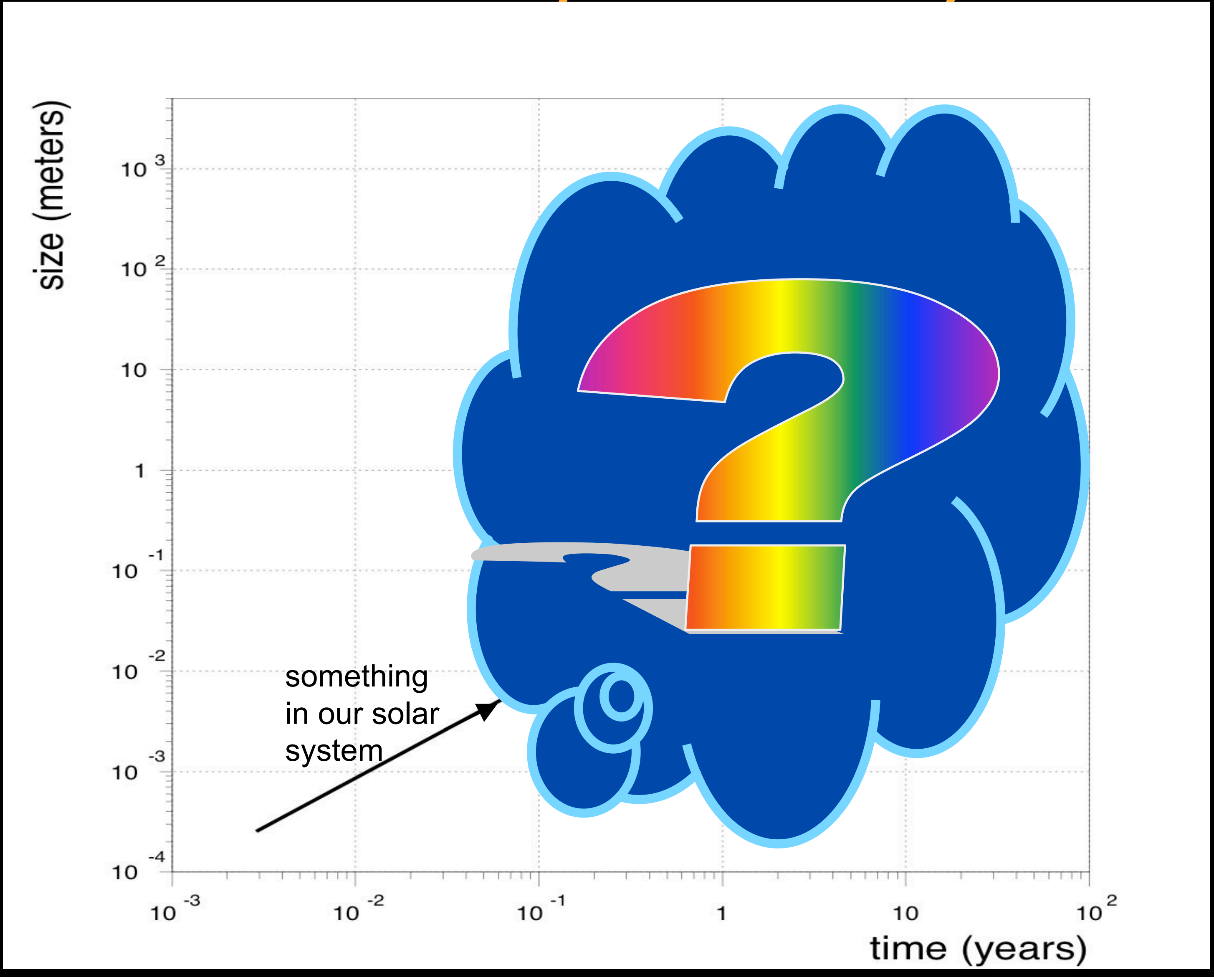
Contents

- Dark Energy Intro
- SDSS Supernova Survey (2005-07)
- SN Ia Rate versus Redshift
- Hubble Diagram Analysis & Results (1st-year SDSS data + external)

Primary Motivation for Supernova Surveys:

measure expansion
history of the Universe:
in particular, the role of
dark energy

Understanding Expansion History is Tricky



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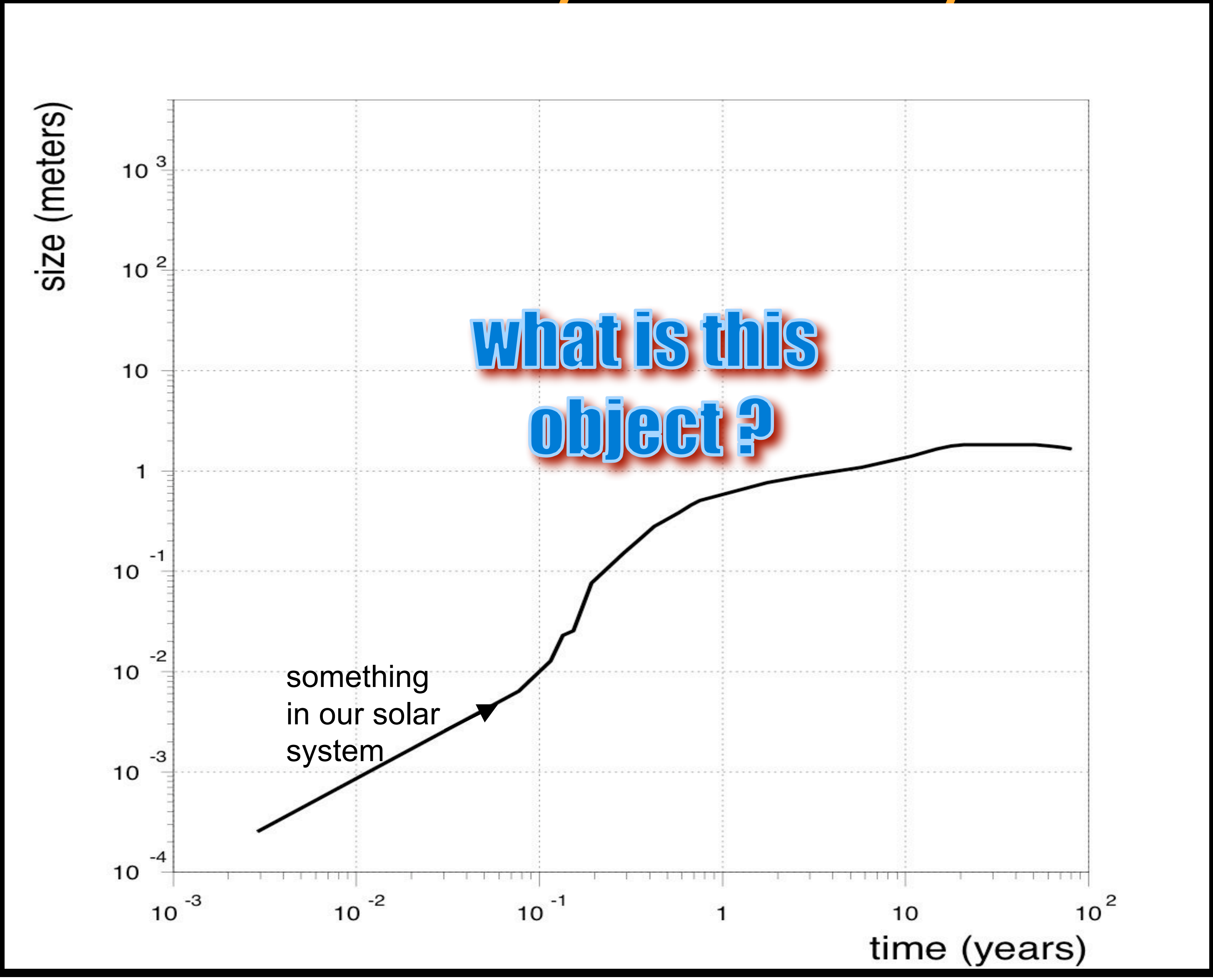

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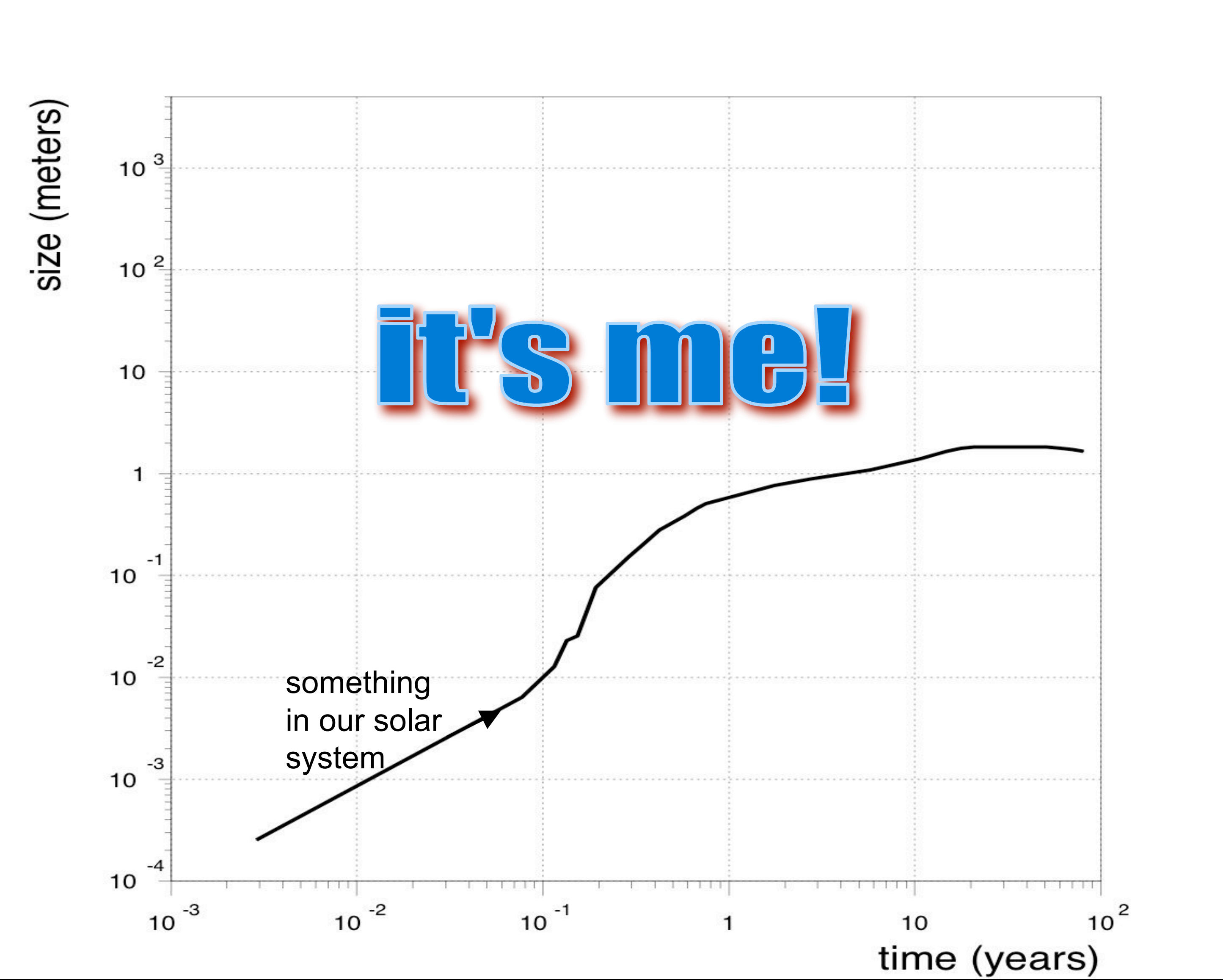

Fun Facts About Dark Energy

- $\rho_\Lambda = 10^{-29}$ g/cm^3 everywhere.
- Earth volume contains 0.01g of dark energy.
- Dark energy increases Earth's orbit by 0.1μm; Pluto's orbit is increased by 1μm.
- Gravity and dark energy roughly cancel for Milky-Way and Andromeda galaxies (but galaxy-cluster gravity wins)
- $\Omega_\Lambda = 0.7$ today
- $\Omega_\Lambda/\Omega_M \sim 2.3$ today (compare $\Omega_\gamma/\Omega_M < 10^{-4}$).
- $\Omega_\Lambda = \Omega_M$ at z=0.3 (3-4 billion years ago, assumes w=-1).
- Undetectable in terrestrial experiments (so far).
- Nobody knows what dark energy (or dark matter) is.

Expansion Basics

$H(z)^2 = H_0^2 \, \Sigma_i \, \Omega_i \, (1+z)^{3(1+w)}$

[where $w = p/\rho$, and $R = 1/(1+z)$]

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Source of expansion	**w**	**Evolution with z**	**Ω at z=0**
Matter (dark, baryon, relic ν)	$v^2/c^2 \sim 0$	$\Omega_M(1+z)^3$	0.3
Radiation (CMB)	1/3	$\Omega_\gamma(1+z)^4$	$\sim 10^{-5}$
Cosmological constant (?)	–1	Ω_Λ = constant	0.7
Curvature	–1/3	$\Omega_k(1+z)^2$	< few %

Methods to Measure H(z)

$H(z)^2 = \Sigma_i \, \Omega_i \, (1+z)^{3(1+w)}$

Method	Difficulties
brightness vs. redshift	Large dispersion in brightness. Evolution ? Dust ?
count galaxy clusters vs redshift.	Need to know cluster-mass selection function.
galaxy clustering; power spectrum or clumpiness	galaxy vs. dark matter clustering
Weak lensing	Systematics of galaxy-shear measurements

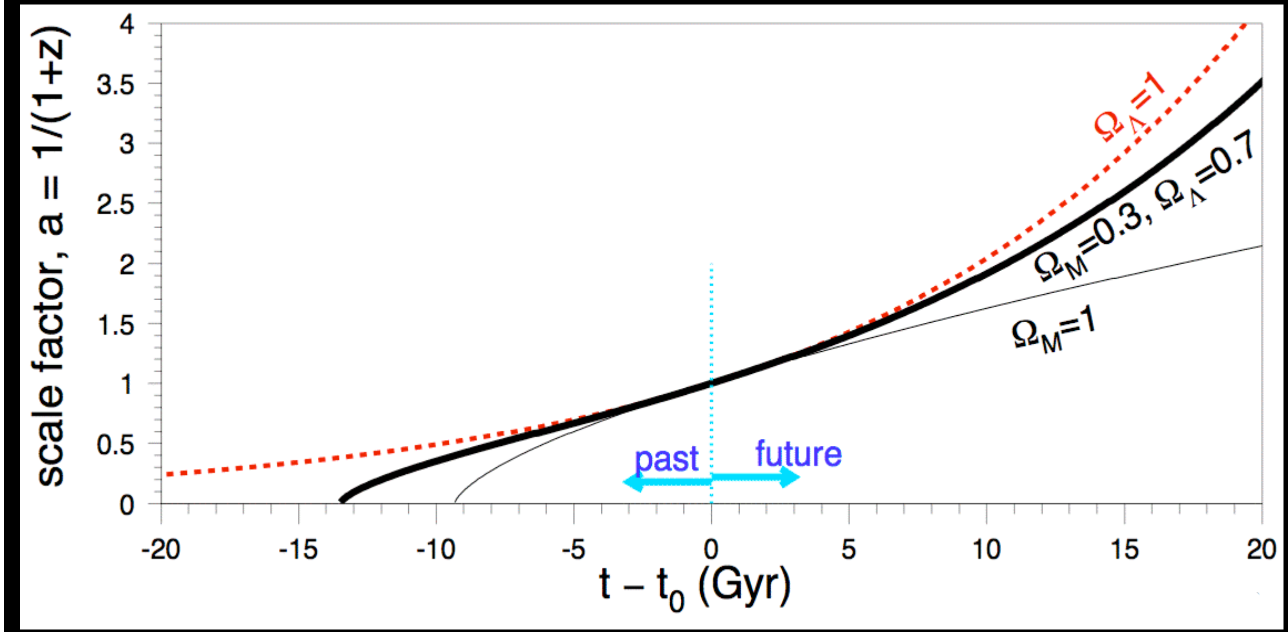
Methods to Measure H(z)

$$H(z)^2 = \Sigma_i \, \Omega_i \, (1+z)^{3(1+w)}$$

Method	Difficulties
brightness vs. redshift for **SN Ia**	~~Large dispersion in brightness.~~ Evolution ? Dust ?

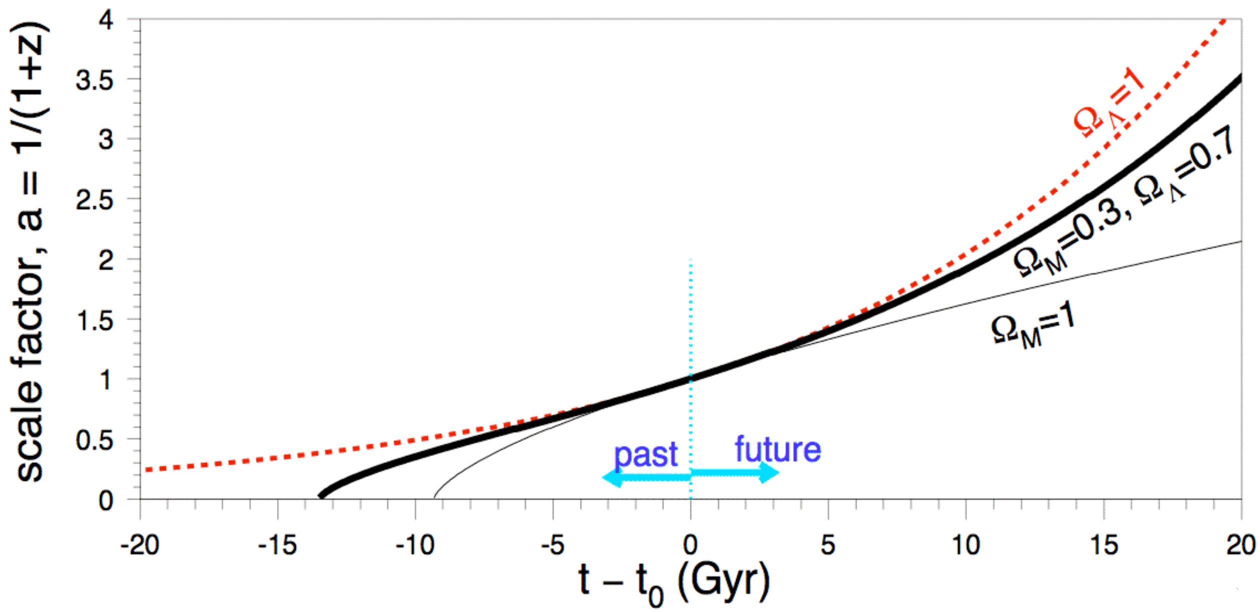
Natural dispersion ~ factor of 2 :
reduced to 15% after ‘width-luminosity’ correction (Phillips 1993)

Hubble Diagram Basics



Expansion history depends on Ω_Λ and Ω_M

Hubble Diagram Basics



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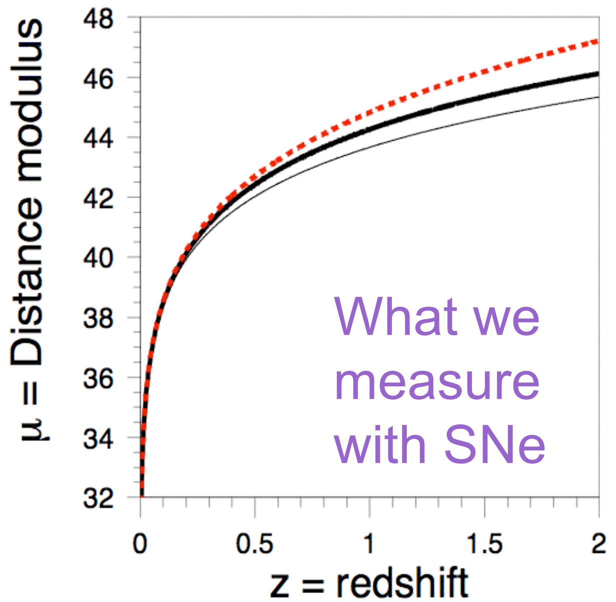
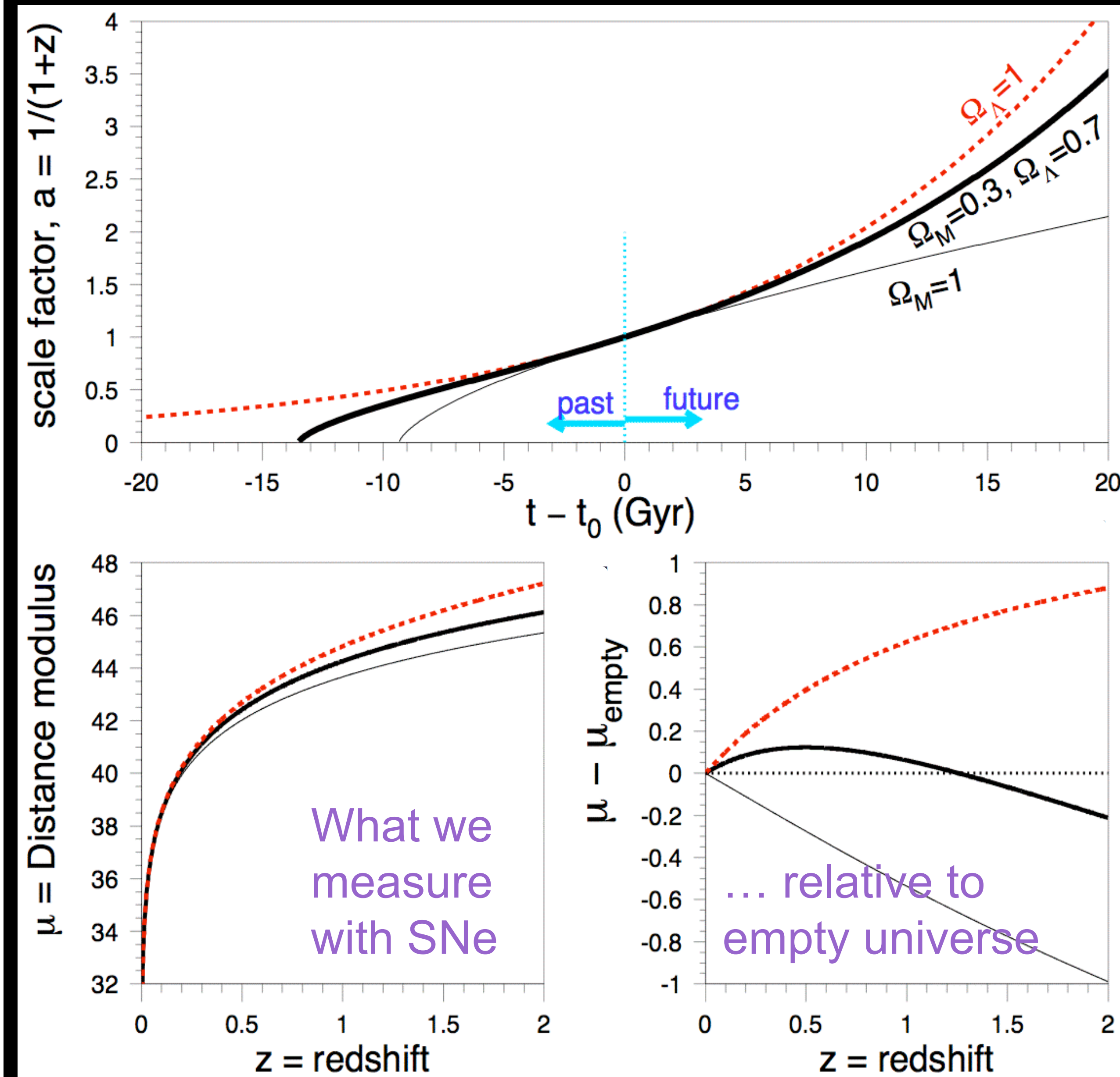


$\text{mag} = -2.5\log(\mathscr{L}/4\pi d_L^2)$.

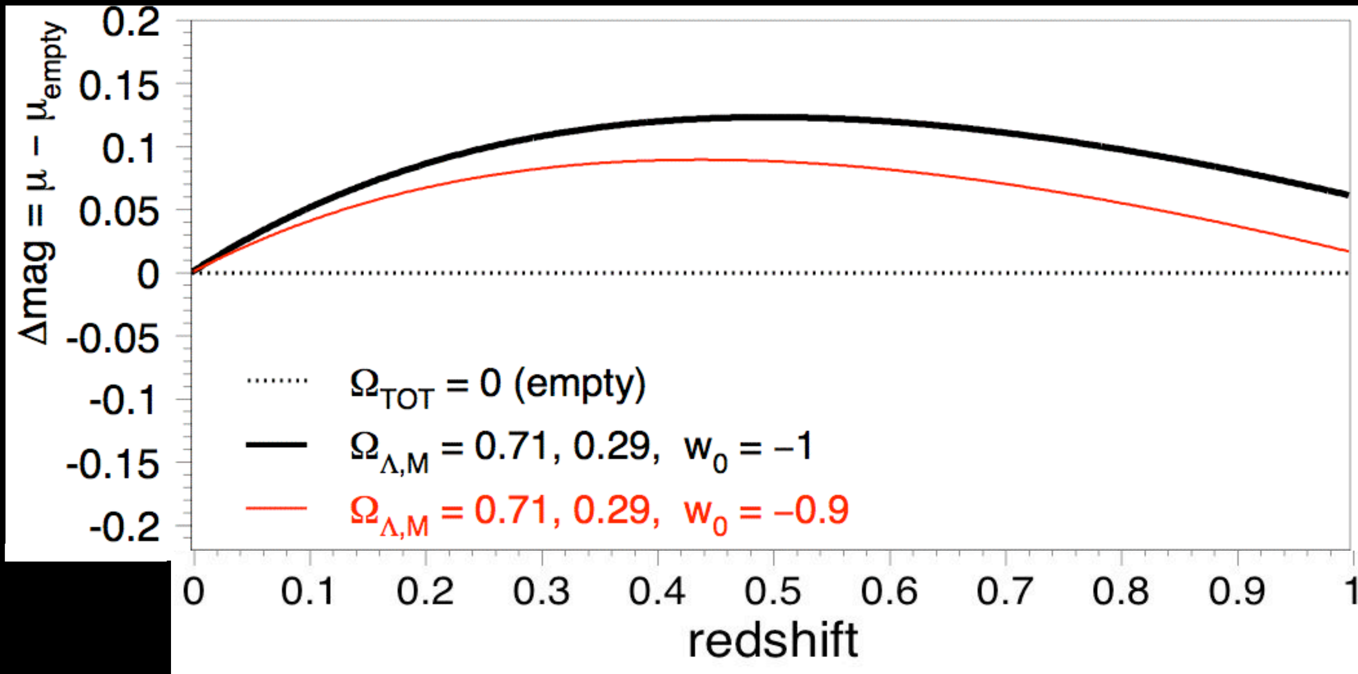
$d_L = (1+z) \int dz/H(z,\Omega_M,\Omega_\Lambda,w)$
for flat universe.
Distance modulus: $\mu = 5\log(d_L/10\text{pc})$

Hubble Diagram Basics

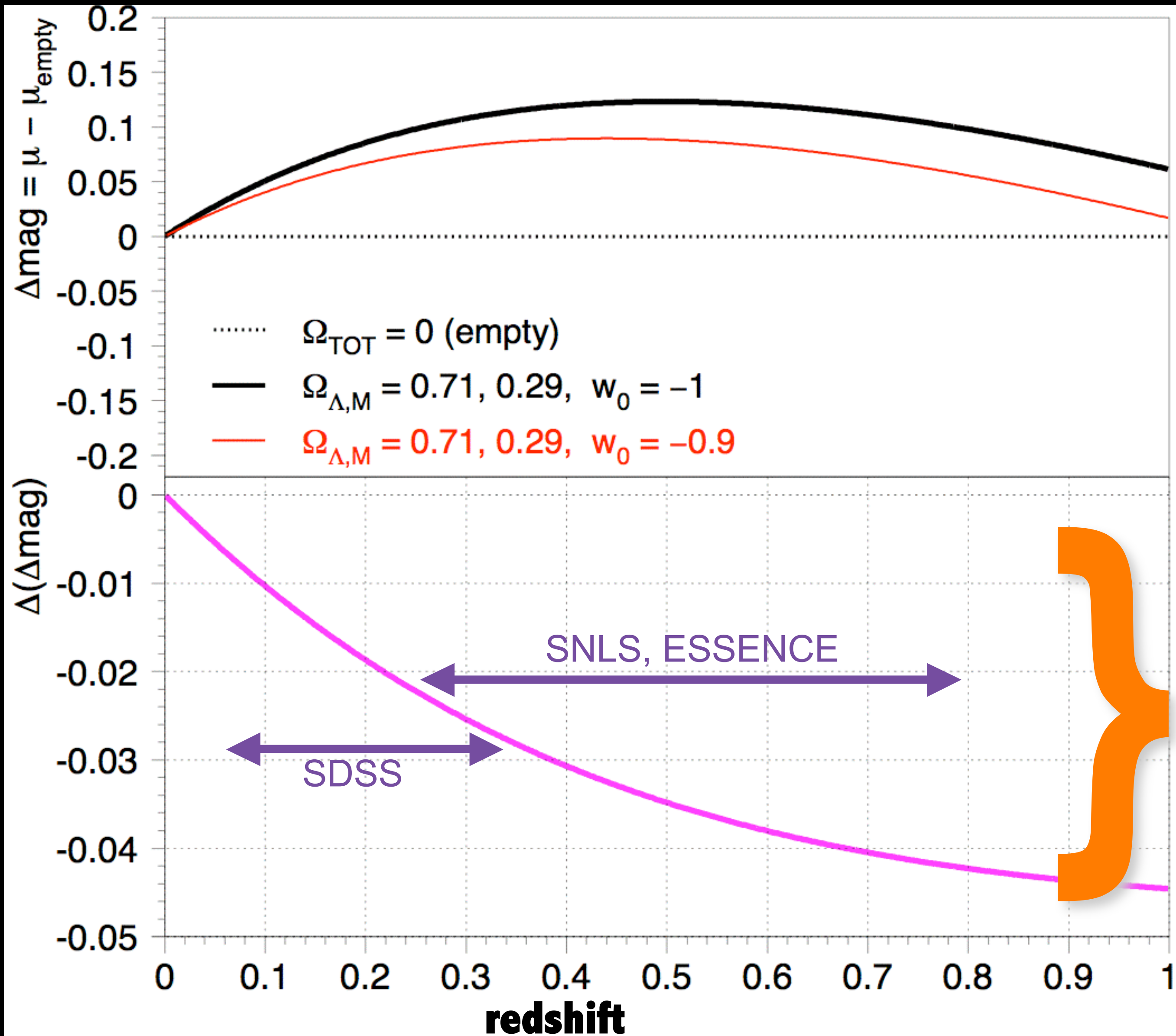


Expansion history depends on Ω_Λ and Ω_M

w-sensitivity with Supernova



w-Quest with Supernova

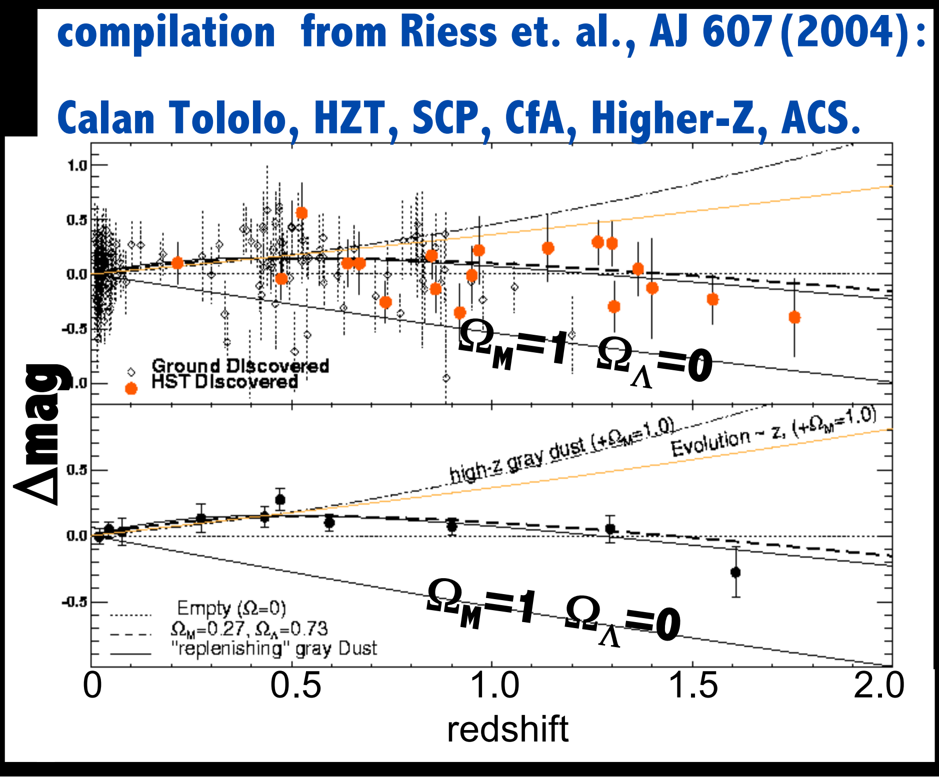


w = –0.9 gives 4% variation from w = –1

Surveys

1990s

Development & discovery phase (Hi-z, SCP).
Lightcurve quality limited by telescope time.



Surveys

1990s

Development & discovery phase (Hi-z, SCP).
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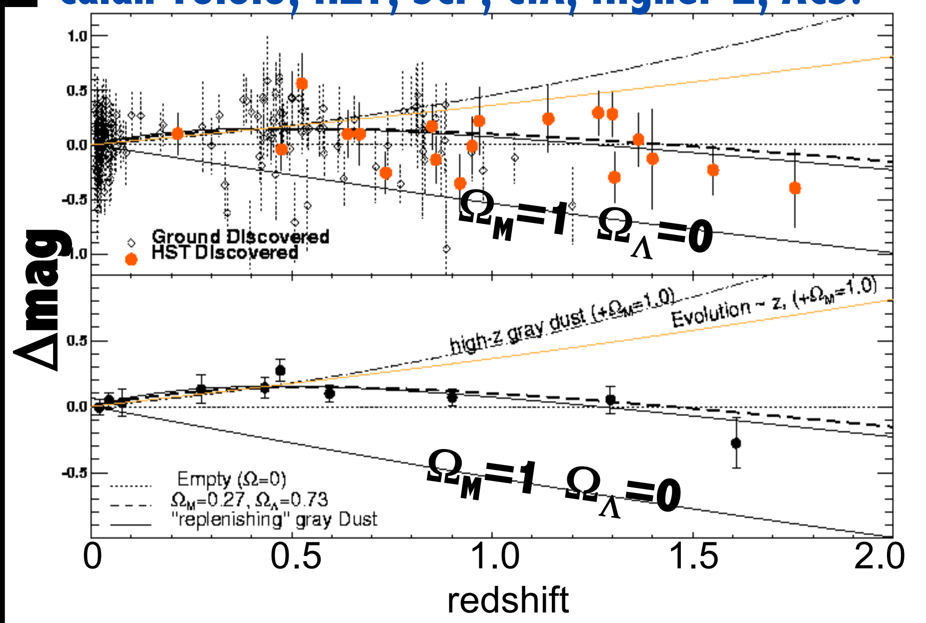
2000s

Much more telescope time ➨ rolling searches & more passbands.
(SNLS, ESSENCE, SDSS)

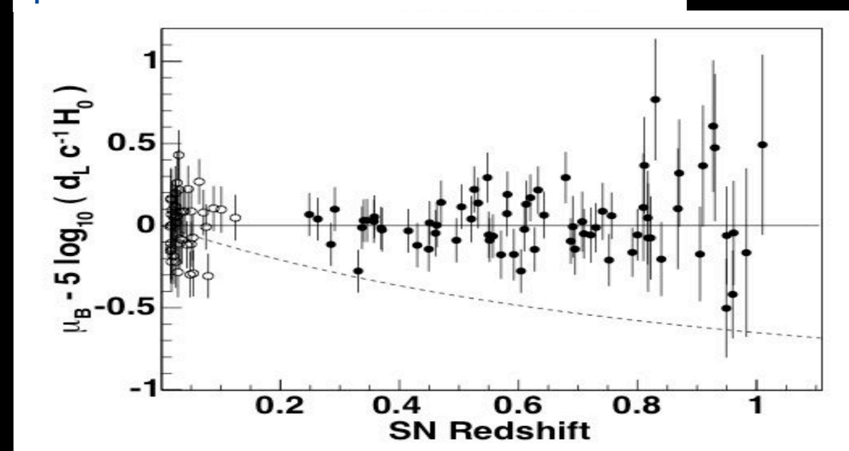
compilation from Riess et. al., AJ 607 (2004):

Calan Tololo, HZT, SCP, CfA, Higher-Z, ACS.



SNLS 1st year sample (Astier 2005)

plus ~ 40 low-z SNe from literature



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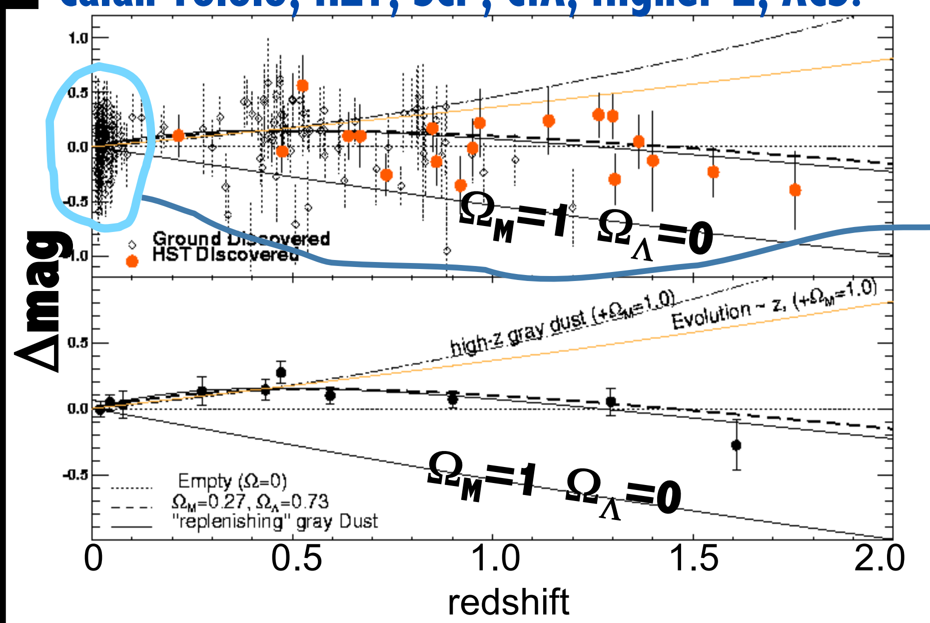

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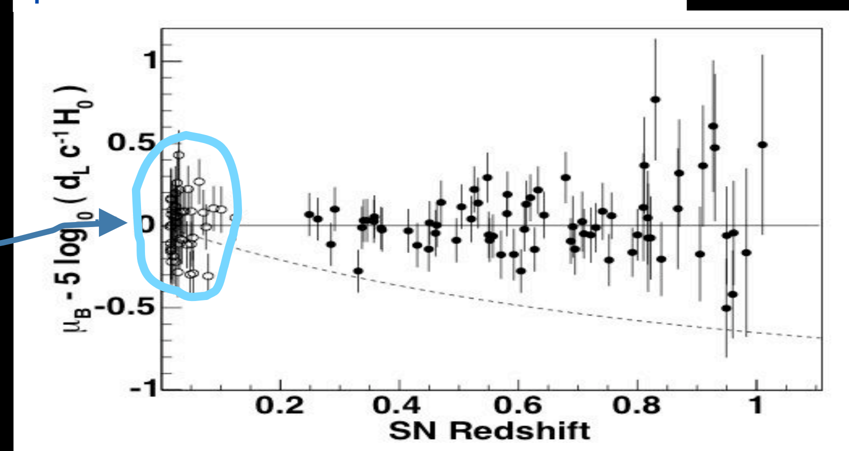

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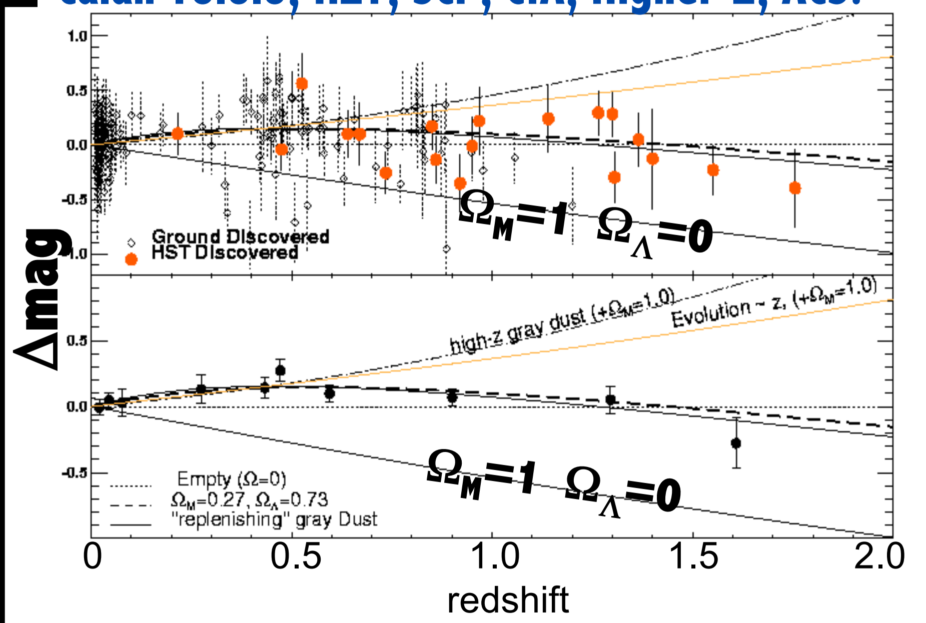

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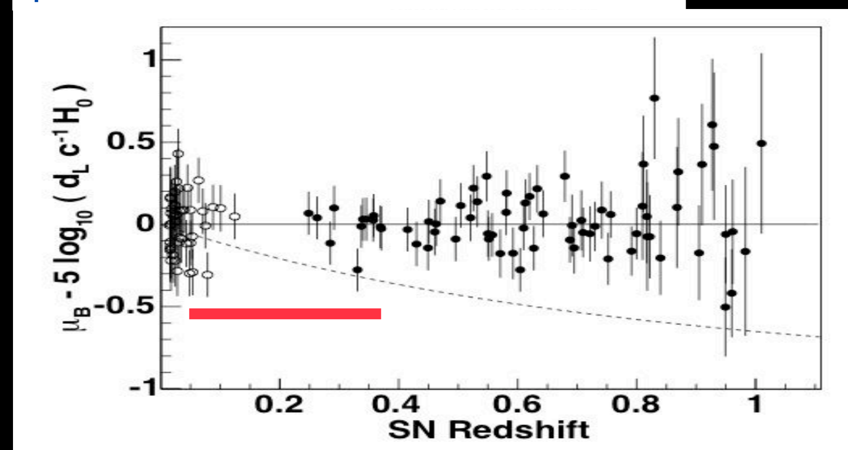


SDSS survey fills gap & adds low-z SNe

SDSS

SN papers becoming "Methodology" papers as surveys contribute smaller fraction of total SNe Ia

- Astier06: SNLS contributes ~ 70 of 110
- Kowalski 2008:

  contributes 8 of 307 SNe Ia
- SDSS 2009: contributes 103 of 288

Meet the SDSS-II Supernova Team

The Sloan Digital Sky Survey-II Supernova Survey: Technical Summary **AJ 135, 338 (2008)**

Joshua A. Frieman,[1,2,3] Bruce Bassett,[4,5] Andrew Becker,[6] Changsu Choi,[7] David Cinabro,[8] Fritz DeJongh,[1] Darren L. Depoy,[9] Ben Dilday,[2,10] Mamoru Doi,[11] Peter M. Garnavich,[12] Craig J. Hogan,[6] Jon Holtzman,[13] Myungshin Im,[7] Saurabh Jha,[14] Richard Kessler,[2,15] Kohki Konishi,[16] Hubert Lampeitl,[17] John Marriner,[1] Jennifer L. Marshall,[9] David McGinnis,[1] Gajus Miknaitis,[1] Robert C. Nichol,[18] Jose Luis Prieto,[9] Adam G. Riess,[17,19] Michael W. Richmond,[20] Roger Romani,[14] Masao Sako,[21] Donald P. Schneider,[22] Mathew Smith,[18] Naohiro Takanashi,[11] Kouichi Tokita,[11] Kurt van der Heyden,[5] Naoki Yasuda,[16] Chen Zheng,[14] Jennifer Adelman-McCarthy,[1] James Annis,[1] Roberto J. Assef,[9] John Barentine,[23,24] Ralf Bender,[25,26] Roger D. Blandford,[14] William N. Boroski,[1] Malcolm Bremer,[27] Howard Brewington,[24] Chris A. Collins,[28] Arlin Crotts,[29] Jack Dembicky,[24] Jason Eastman,[9] Alastair Edge,[30] Edmond Edmondson,[18] Edward Elson,[5] Michael E. Eyler,[31] Alexei V. Filippenko,[32] Ryan J. Foley,[32] Stephan Frank,[9] Ariel Goobar,[33] Tina Gueth,[13] James E. Gunn,[34] Michael Harvanek,[24,35] Ulrich Hopp,[25,26] Yutaka Ihara,[11] Želko Ivezić,[6] Steven Kahn,[14] Jared Kaplan,[36] Stephen Kent,[1,3] William Ketzeback,[24] Scott J. Kleinman,[24,37] Wolfram Kollatschny,[38] Richard G. Kron,[3] Jurek Krzesiński,[24,39] Dennis Lamenti,[40] Giorgos Leloudas,[41] Huan Lin,[1] Daniel C. Long,[24] John Lucey,[30] Robert H. Lupton,[34] Elena Malanushenko,[24] Viktor Malanushenko,[24] Russet J. McMillan,[24] Javier Mendez,[42] Christopher W. Morgan,[9,31] Tomoki Morokuma,[11,43] Atsuko Nitta,[24,44] Linda Ostman,[33] Kaike Pan,[24] Constance M. Rockosi,[45] A. Kathy Romer,[46] Pilar Ruiz-Lapuente,[42] Gabrelle Saurage,[24] Katie Schlesinger,[9] Stephanie A. Snedden,[24] Jesper Sollerman,[41,47] Chris Stoughton,[1] Maximilian Stritzinger,[41] Mark SubbaRao,[3] Douglas Tucker,[1] Petri Vaisanen,[5] Linda C. Watson,[9] Shannon Watters,[24] J. Craig Wheeler,[23] Brian Yanny,[1] and Donald York[3,15]

[1]Center for Particle Astrophysics, Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510.

[2]Kavli Institute for Cosmological Physics, The University of Chicago, 5640 South Ellis Avenue Chicago, IL 60637.

[3]Department of Astronomy and Astrophysics, The University of Chicago, 5640 South Ellis Avenue, Chicago, IL 60637.

[4]Department of Mathematics and Applied Mathematics, University of Cape Town, Rondebosch 7701, South Africa.

[5]South African Astronomical Observatory, P.O. Box 9, Observatory 7935, South Africa.

[6]Department of Astronomy, University of Washington, Box 351580, Seattle, WA 98195.

[7]Department of Astronomy, Seoul National University, Seoul, South Korea.

[8]Department of Physics, Wayne State University, Detroit, MI 48202.

[9]Department of Astronomy, Ohio State University, 140 West 18th Avenue, Columbus, OH 43210-1173.

[10]Department of Physics, University of Chicago, Chicago, IL 60637.

[11]Institute of Astronomy, Graduate School of Science, University of Tokyo 2-21-1, Osawa, Mitaka, Tokyo 181-0015, Japan.

[12]University of Notre Dame, 225 Nieuwland Science, Notre Dame, IN 46556-5670.

[13]Department of Astronomy, MSC 4500, New Mexico State University, P.O. Box 30001, Las Cruces, NM 88003.

[14]Kavli Institute for Particle Astrophysics & Cosmology, Stanford University, Stanford, CA 94305-4060.

[15]Enrico Fermi Institute, University of Chicago, 5640 South Ellis Avenue, Chicago, IL 60637.

[16]Institute for Cosmic Ray Research, University of Tokyo, 5-1-5, Kashiwanoha, Kashiwa, Chiba, 277-8582, Japan.

[17]Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218.

[18]Institute of Cosmology and Gravitation, Mercantile House, Hampshire Terrace, University of Portsmouth, Portsmouth PO1 2EG, UK.

[19]Department of Physics and Astronomy, Johns Hopkins University, 3400 North Charles Street, Baltimore, MD 21218.

[20]Physics Department, Rochester Institute of Technology, 85 Lomb Memorial Drive, Rochester, NY 14623-5603.

[21]Department of Physics and Astronomy, University of Pennsylvania, 203 South 33rd Street, Philadelphia, PA 19104.

[22]Department of Astronomy and Astrophysics, The Pennsylvania State University, 525 Davey Laboratory,

+ Steve, Joe, Hal

SDSS-II Supernova Survey: Sep 1 - Nov 30, 2005-2007

(1 of 3 SDSS-II projects for 2005-2008)

GOAL:

Few hundred high-quality type Ia SNe lightcurves in redshift range 0.05-0.4

SAMPLING:

~300 sq deg in ugriz
(3 million galaxies every two nights)

SPECTROSCOPIC FOLLOW-UP:

HET, ARC 3.5m, MDM, Subaru, WHT, Keck, NTT, KPNO, NOT, SALT, Magellan, TNG

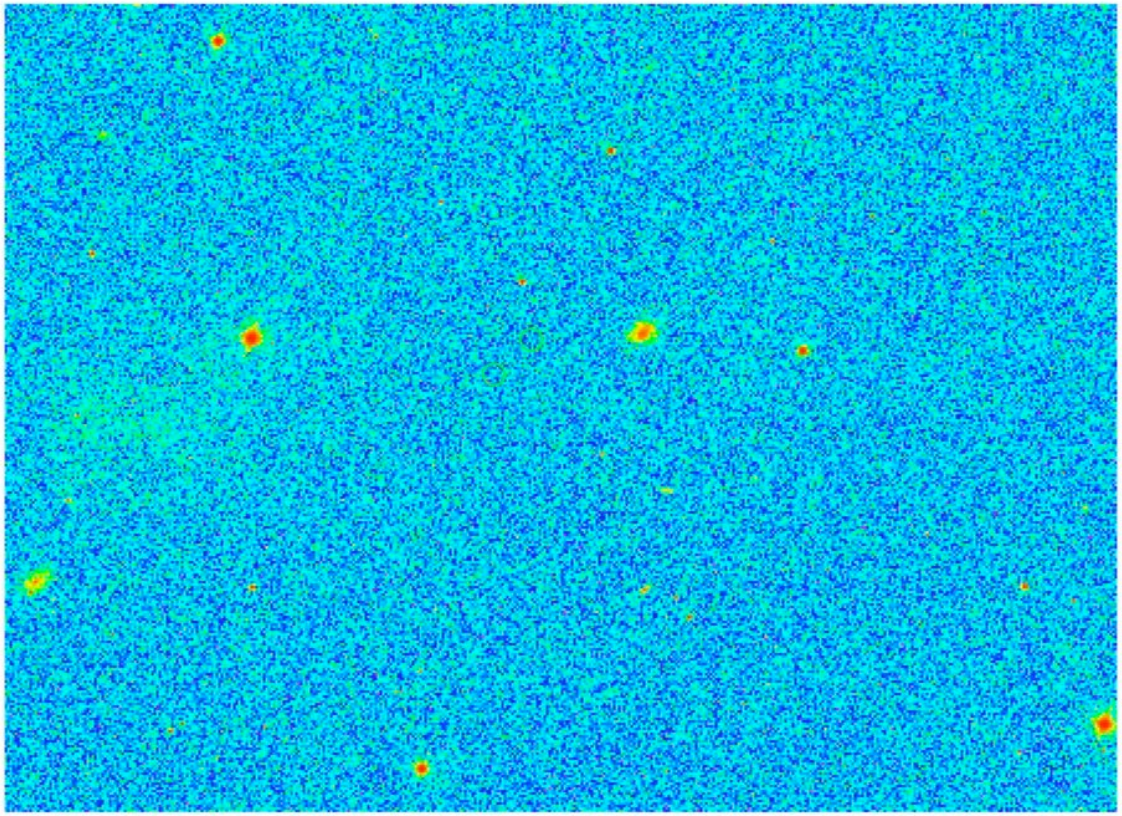
SDSS Data Flow

One full night collects 800 fields (ugriz per field) ➪ 200 GB

Each 'search' field is compared to a 2-year old 'template' field … things that go "boom" are extracted for human scanning.

Ten dual-CPU servers at APO process g,r,i data (2400 fields) in ~ 20 hrs.

one raw g-field (0.15^0)



(can you find a confirmed SN Ia ?)

SDSS Data Flow

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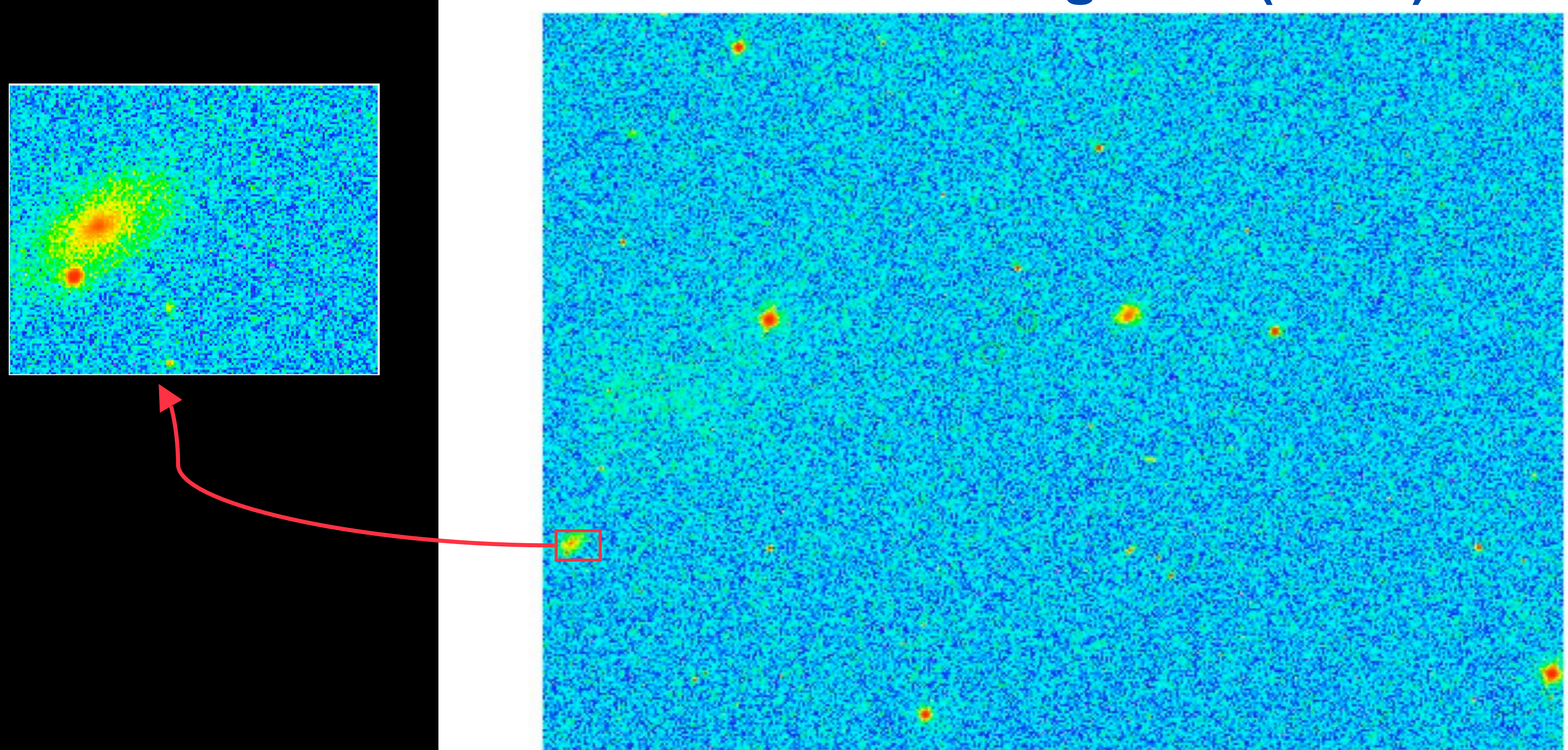
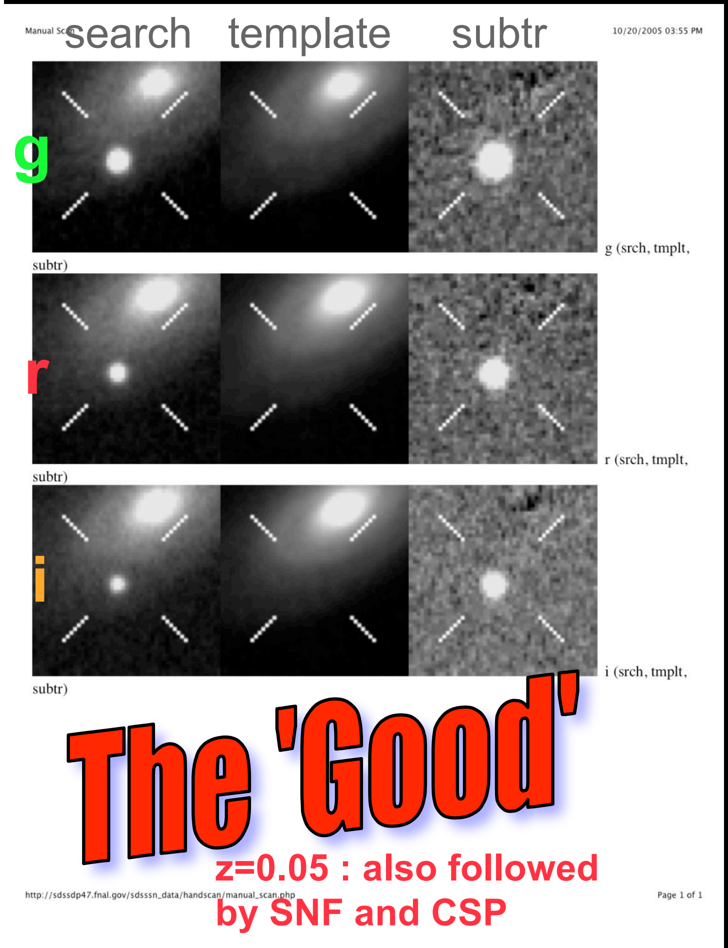
one raw g-field (0.15^0)



SDSS Manual Scanning



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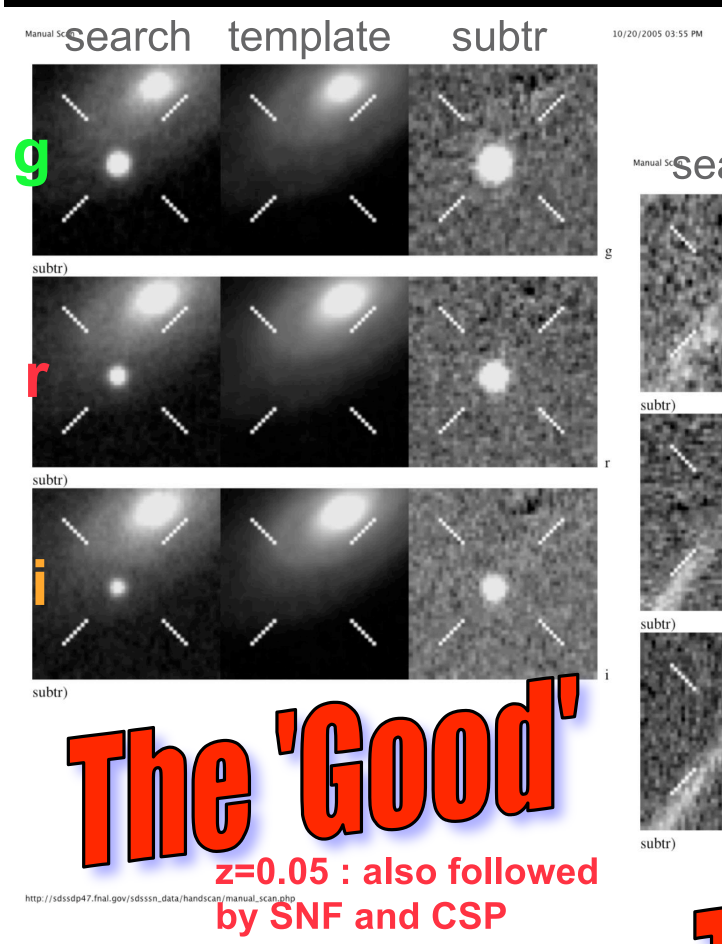

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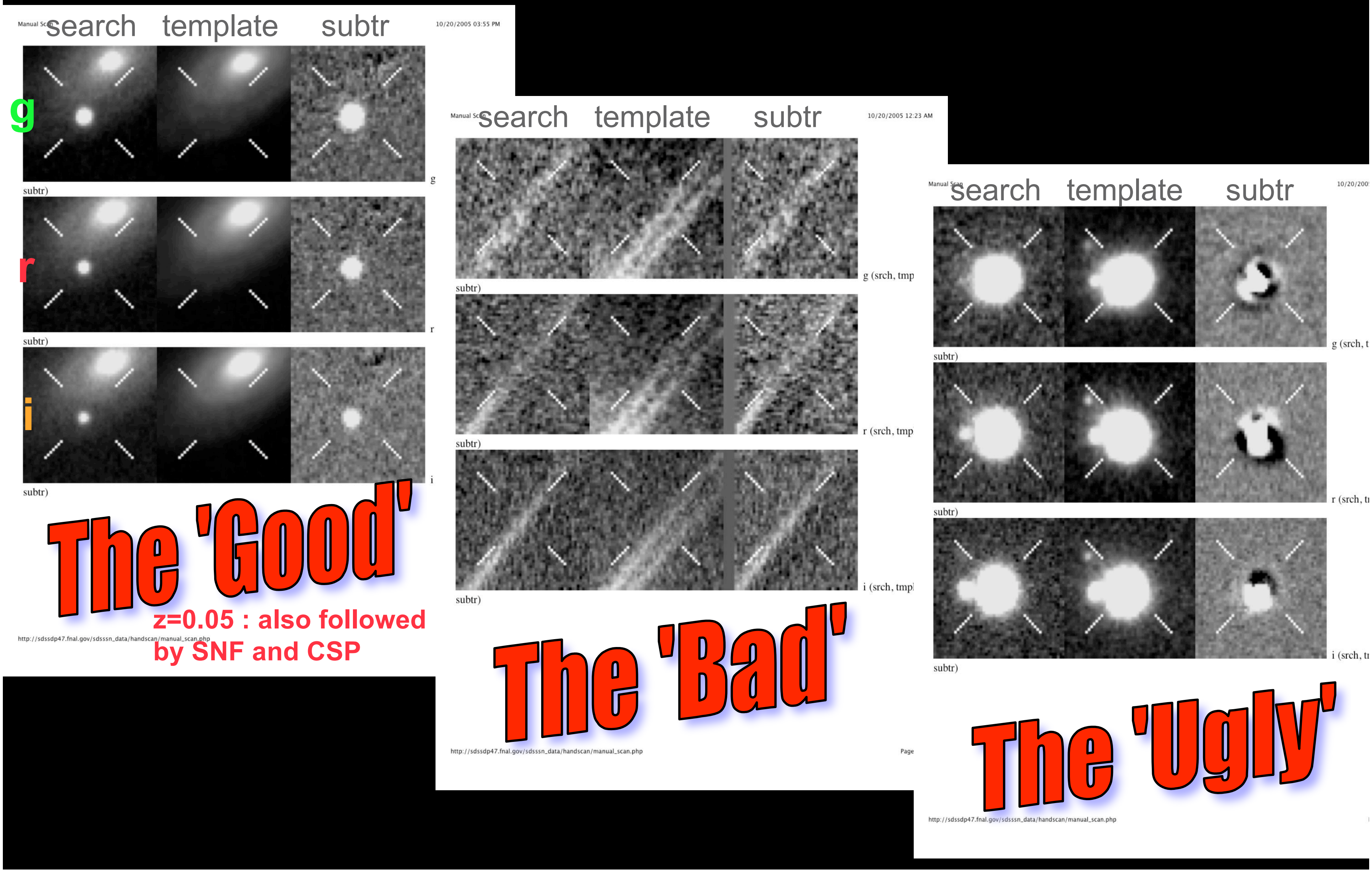
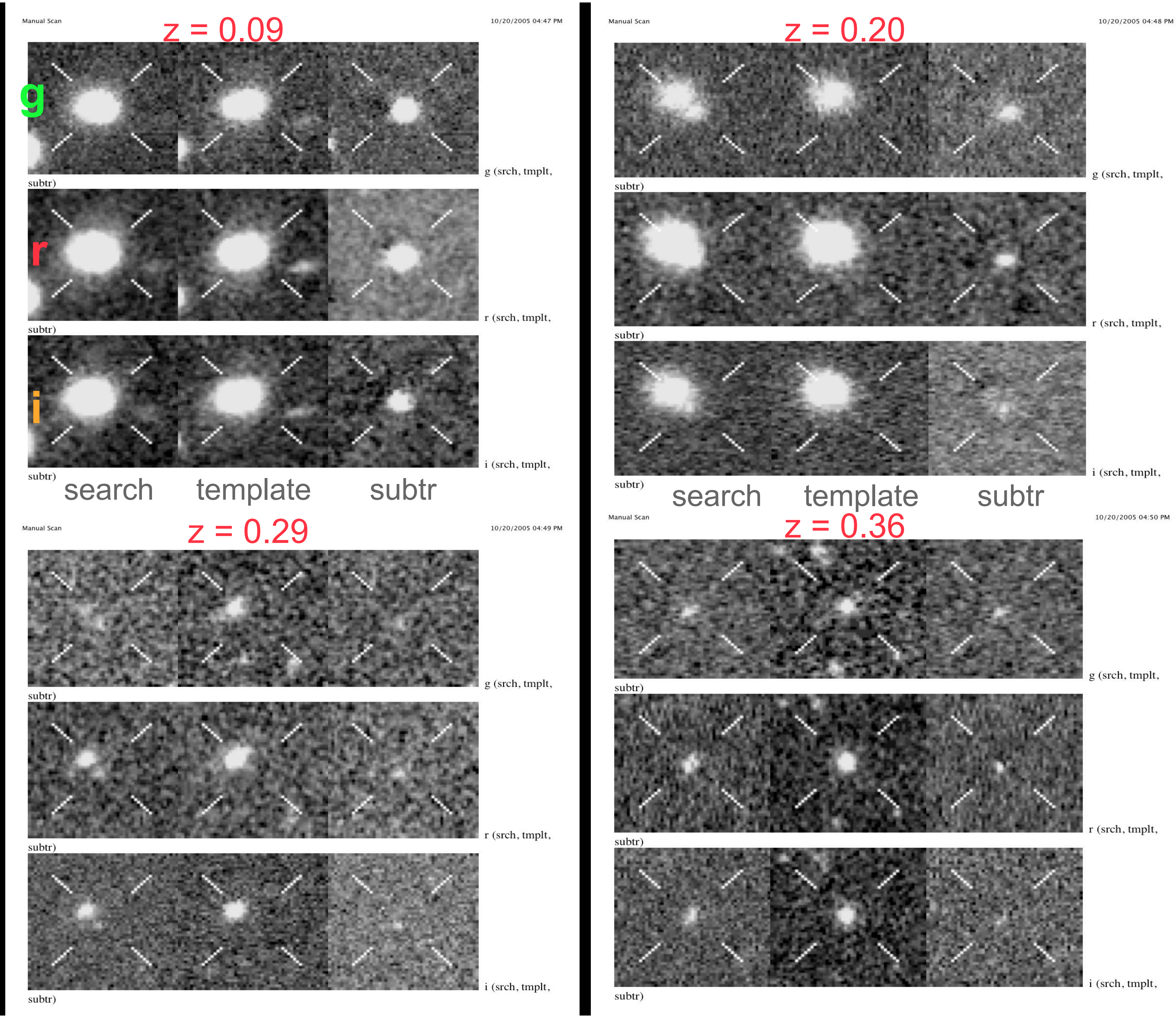




Manual Scan
z = 0.09
10/20/2005 04:47 PM
g
r
i
g (srch, tmplt, subtr)
r (srch, tmplt, subtr)
i (srch, tmplt, subtr)
search
template
subtr
Manual Scan
z = 0.20
10/20/2005 04:48 PM
g (srch, tmplt, subtr)
r (srch, tmplt, subtr)
i (srch, tmplt, subtr)
search
template
subtr
Manual Scan
z = 0.29
10/20/2005 04:49 PM
g (srch, tmplt, subtr)
r (srch, tmplt, subtr)
i (srch, tmplt, subtr)
Manual Scan
z = 0.36
10/20/2005 04:50 PM
g (srch, tmplt, subtr)
r (srch, tmplt, subtr)
i (srch, tmplt, subtr)

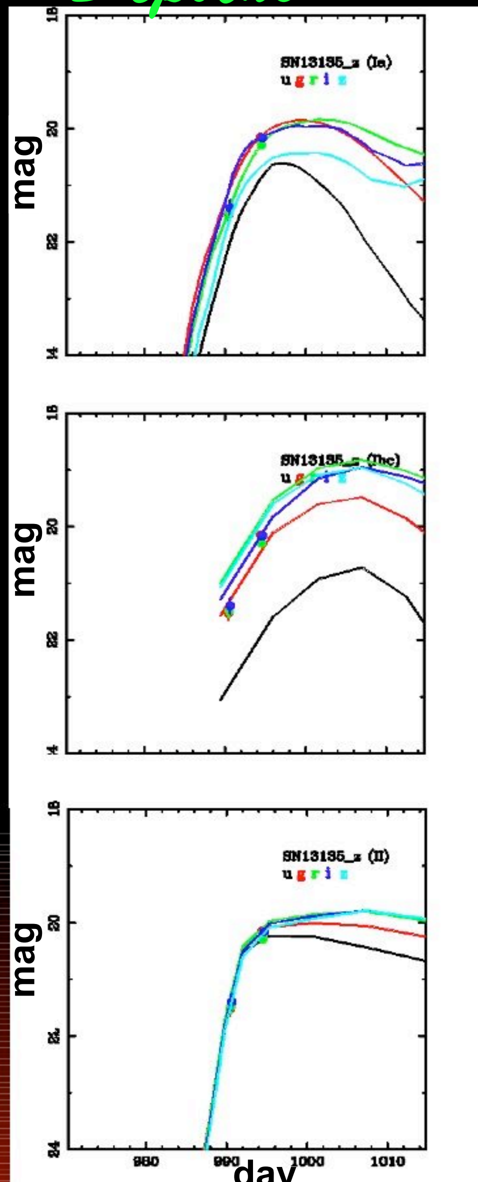
Lightcurve Fits Update in Real Time

2 epochs

SN Ia Fit
$\chi^2 = 1.8$

SN Ibc Fit
$\chi^2 = 39$

SN II Fit
$\chi^2 = 6.6$

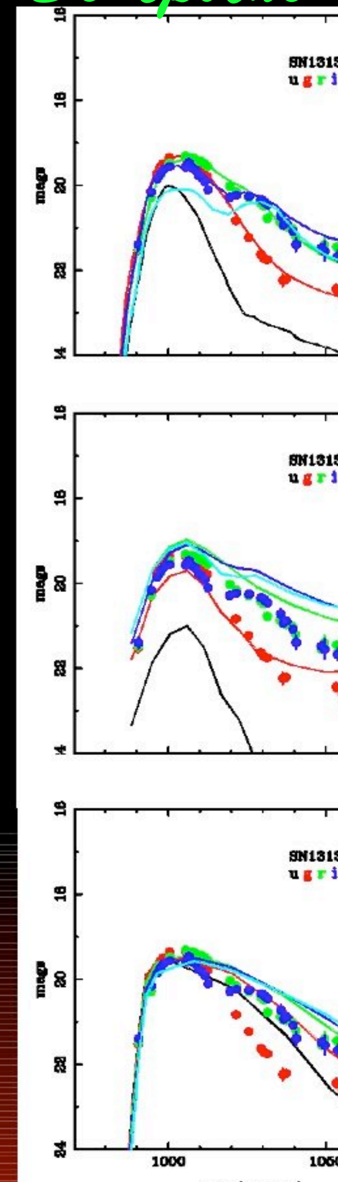


30 epochs

SN Ia Fit
$\chi^2 = 8.8$

SN Ibc Fit
$\chi^2 = 352$

SN II Fit
$\chi^2 = 57$



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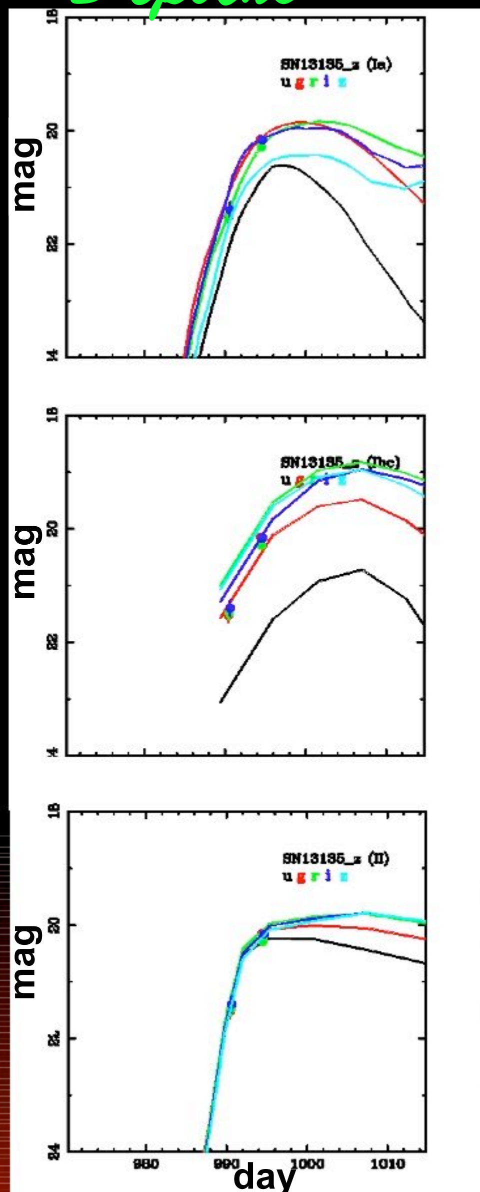
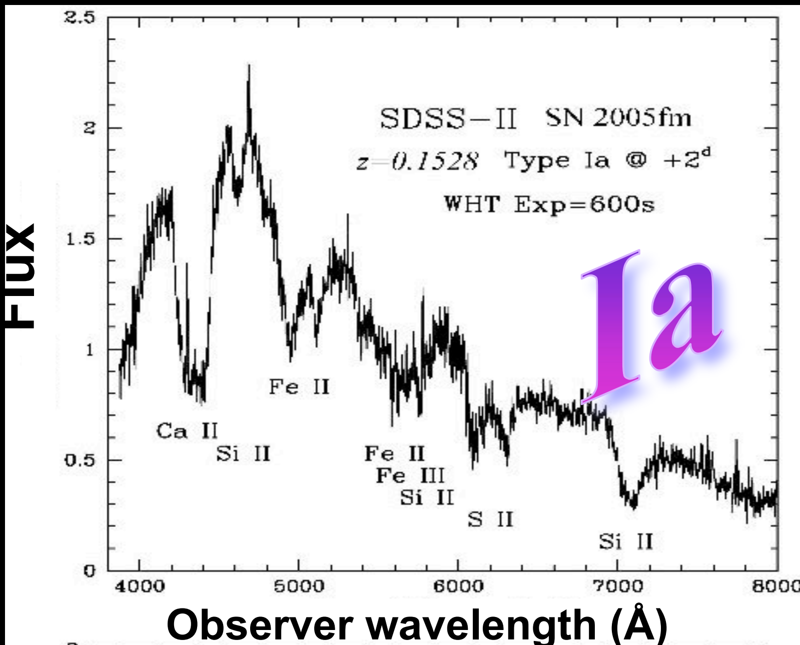
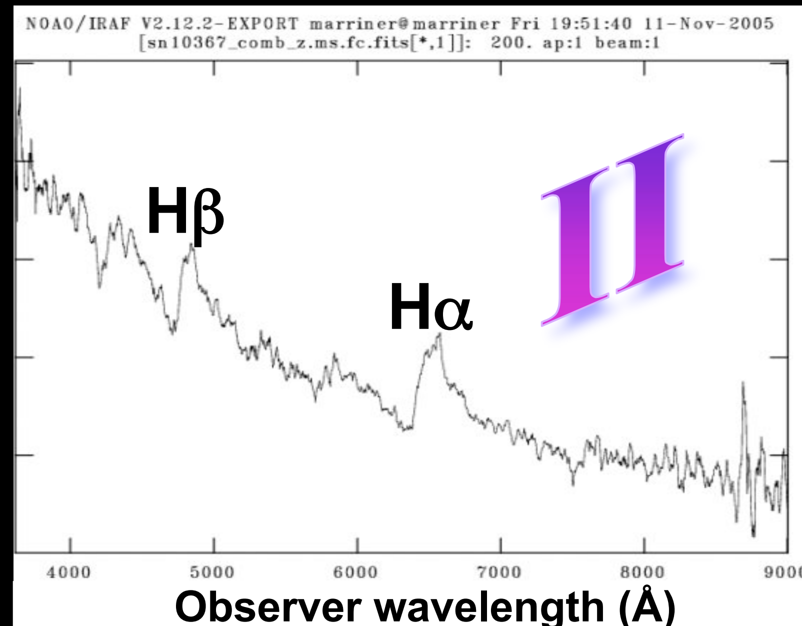
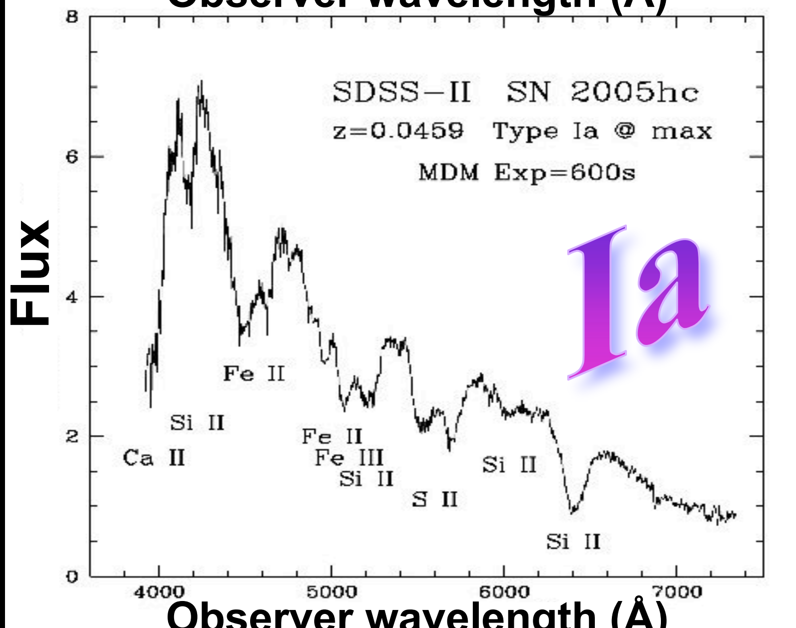


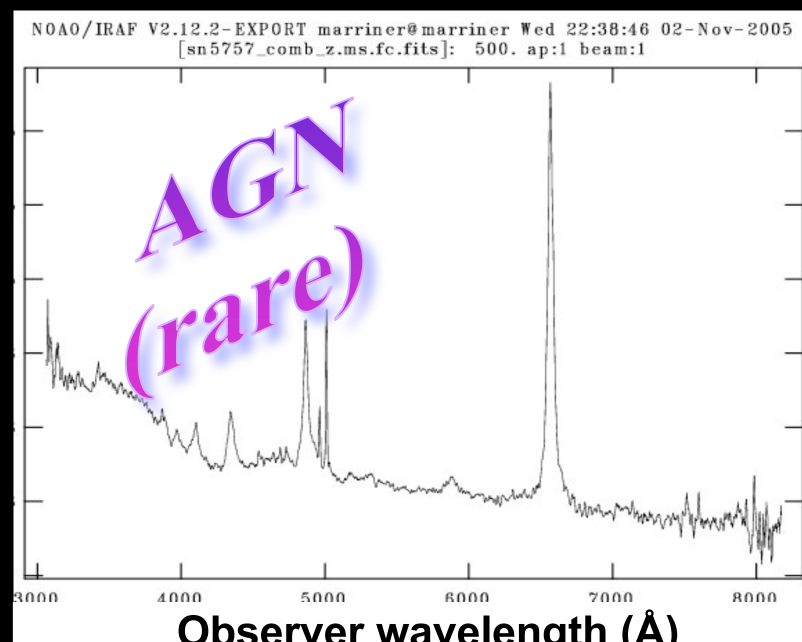
> 90% of photometric Ia candidates were spectroscopically confirmed to be SN Ia

Follow-up Spectral id





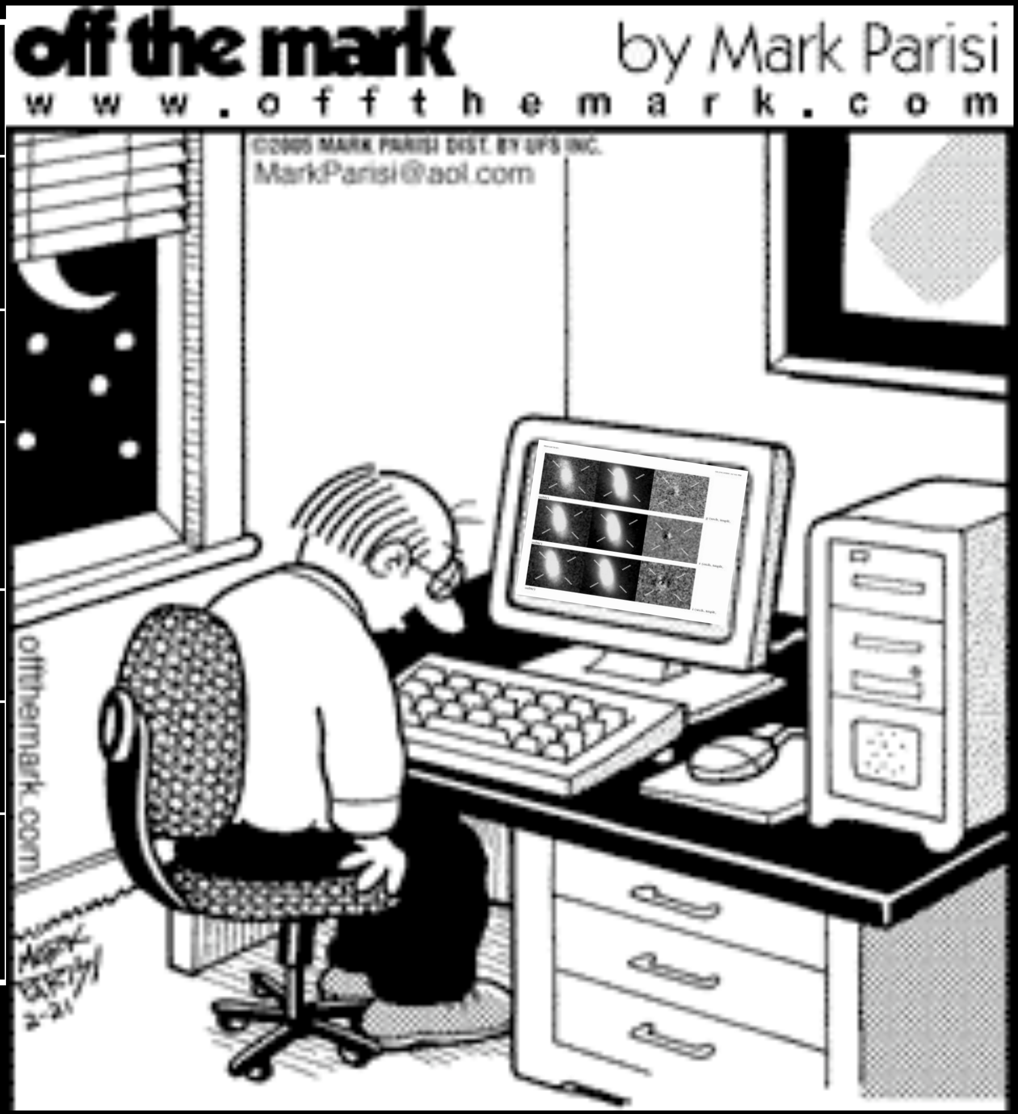




Survey Scan Stats

Sako et al., AJ 135, 348 (2008)

	2005
Objects scanned	140,000
SN candidates	11,400
Candidates with ≥1 spectra	180
Confirmed SN Ia	130
Probable SN Ia	16
Confirmed SN other (Ib, Ic, II)	18



Survey Scan Stats

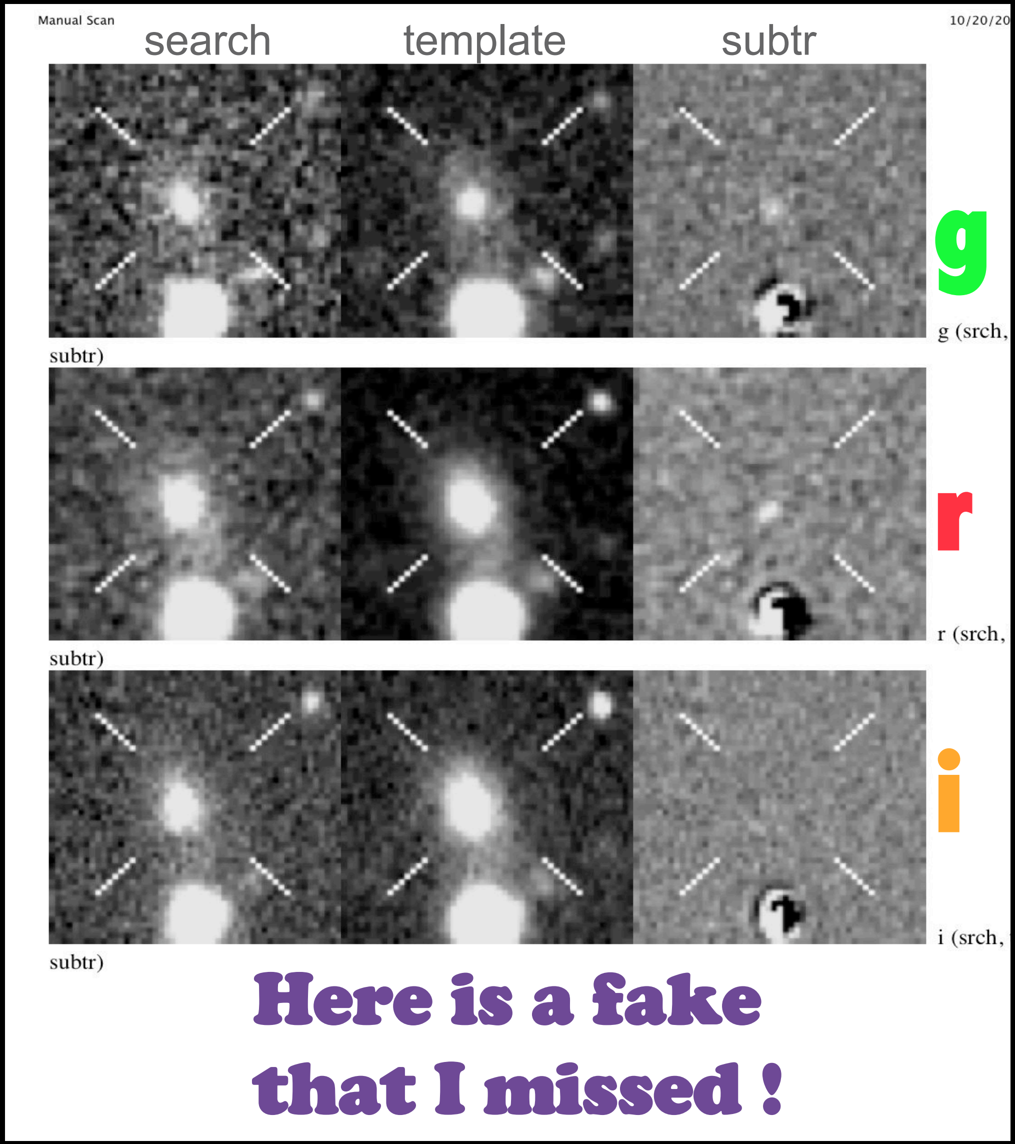
Sako et al., AJ 135, 348 (2008)

	2005	2006	2007	Total
Objects scanned	140,000	14,400	15,200	170,000
SN candidates	11,400	3,700	3,967	19,000
Candidates with ≥1 spectra	180	267	289	736
Confirmed SN Ia	130	197	171	498
Probable SN Ia	16	15	21	52
Confirmed SN other (Ib, Ic, II)	18	37	38	93

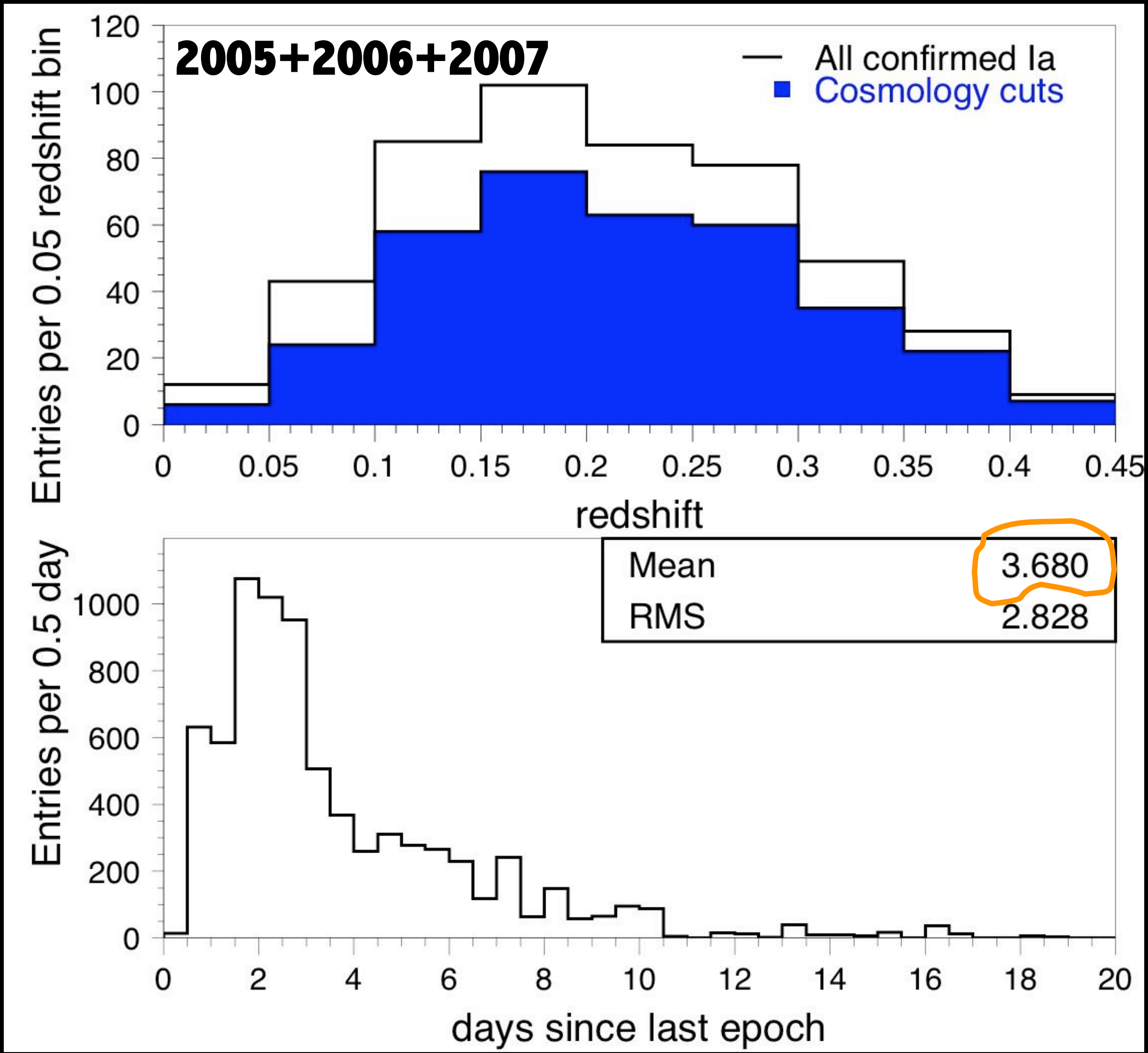
Plus ~ 1000 photometric SN Ia:
we have 300 host-galaxy redshifts and still observing …

SN Fakes

Fake SN Ia were inserted into the images in real time to measure software & scanning efficiencies.



SDSS-SN Redshift & Cadence



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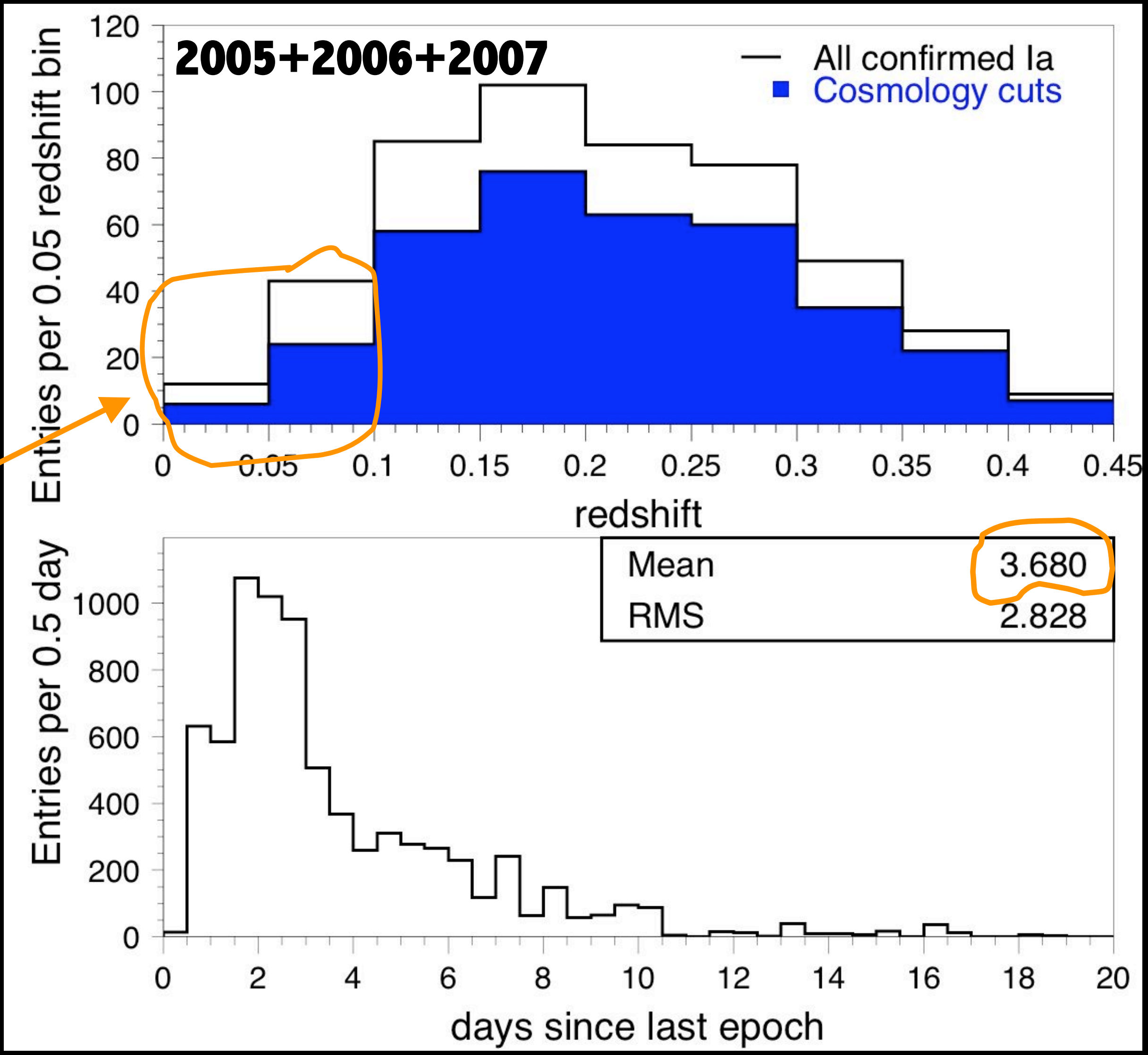
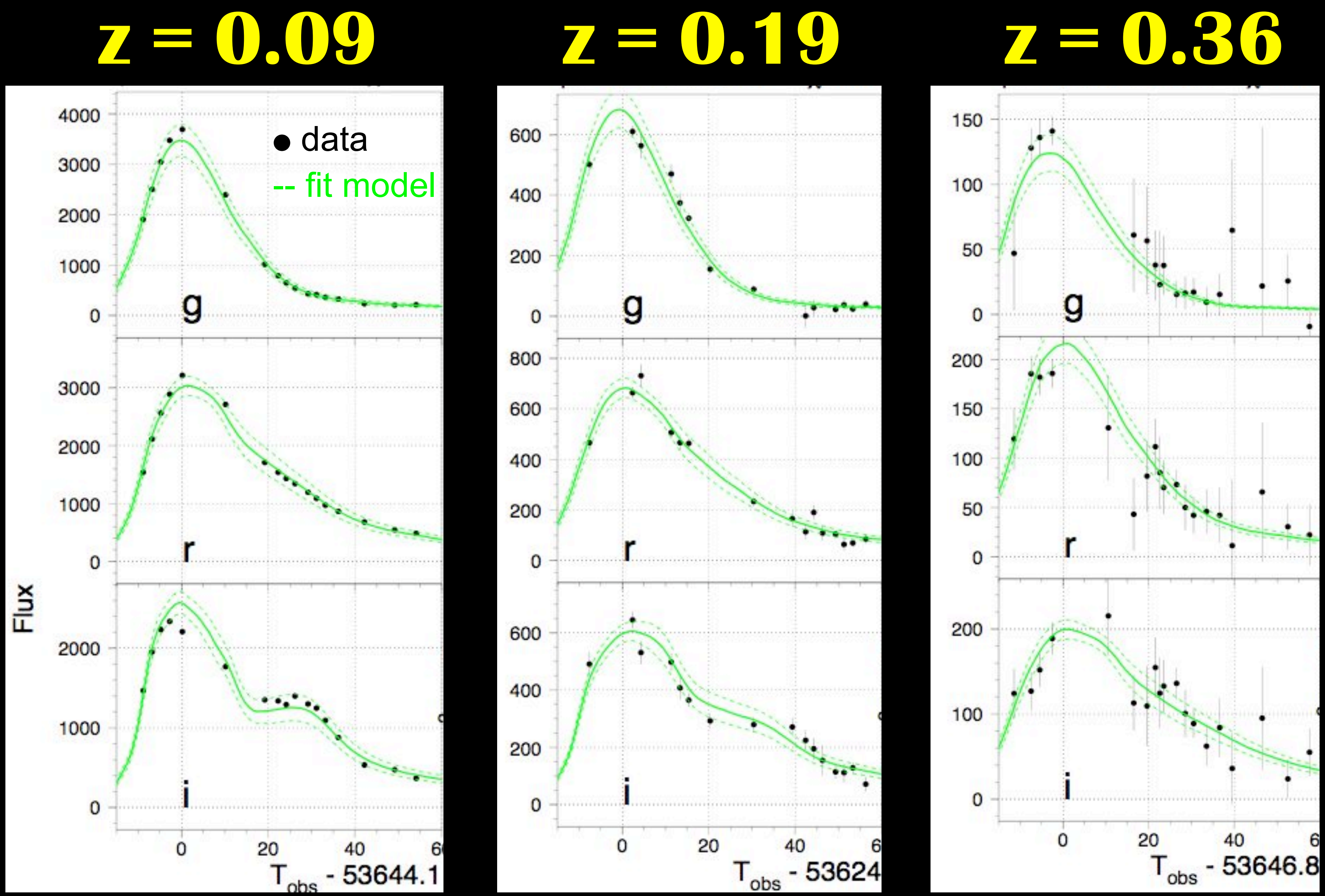


Temporal edge effects: SNe peak too early or too late. May relax cuts later.

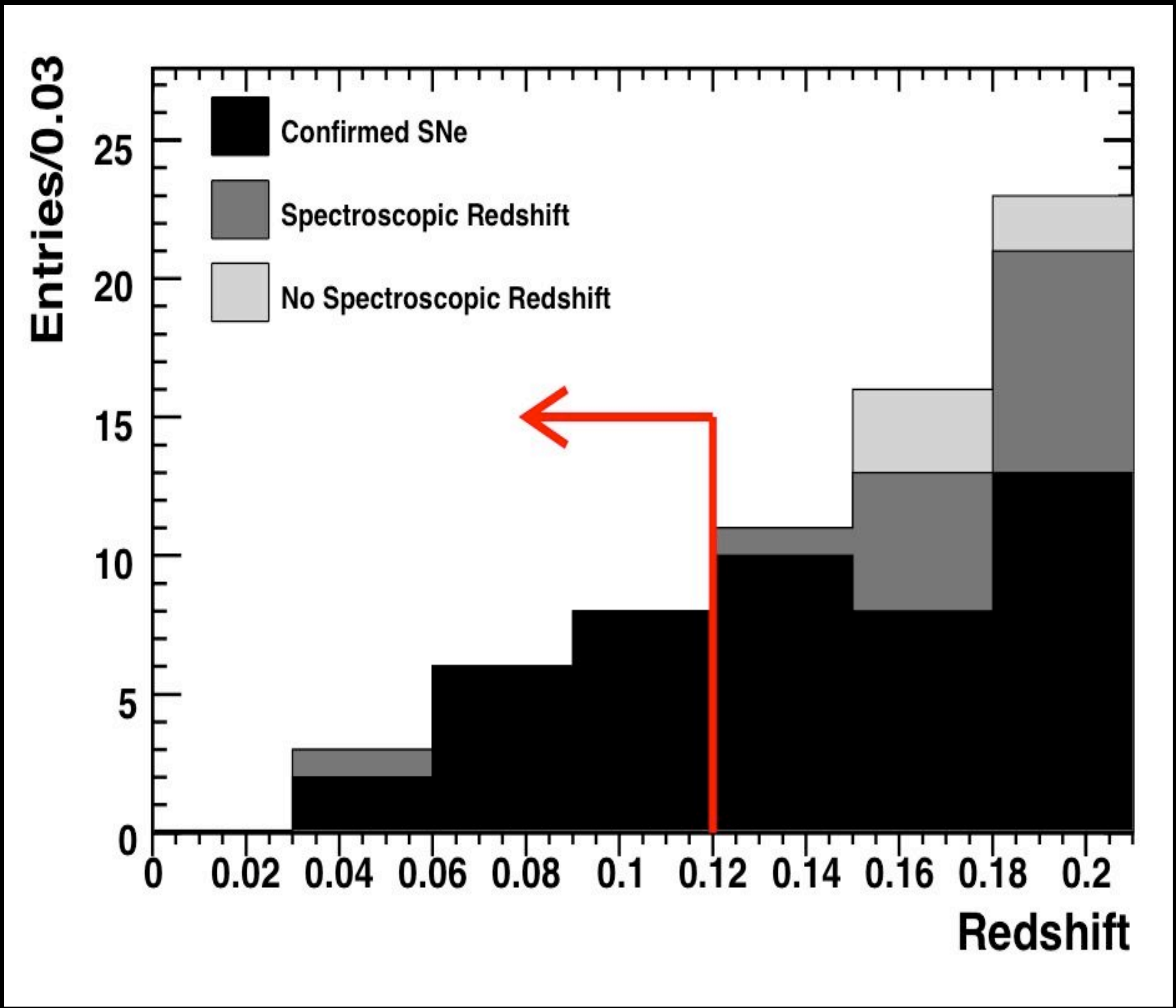
SDSS SN Ia Lightcurves @



SDSS Rate for SN Ia with z < 0.12:

Fall-2005 sample ➜ Dilday et al., arXiv:0801.3297

Motivation: understand nature of SN progenitors

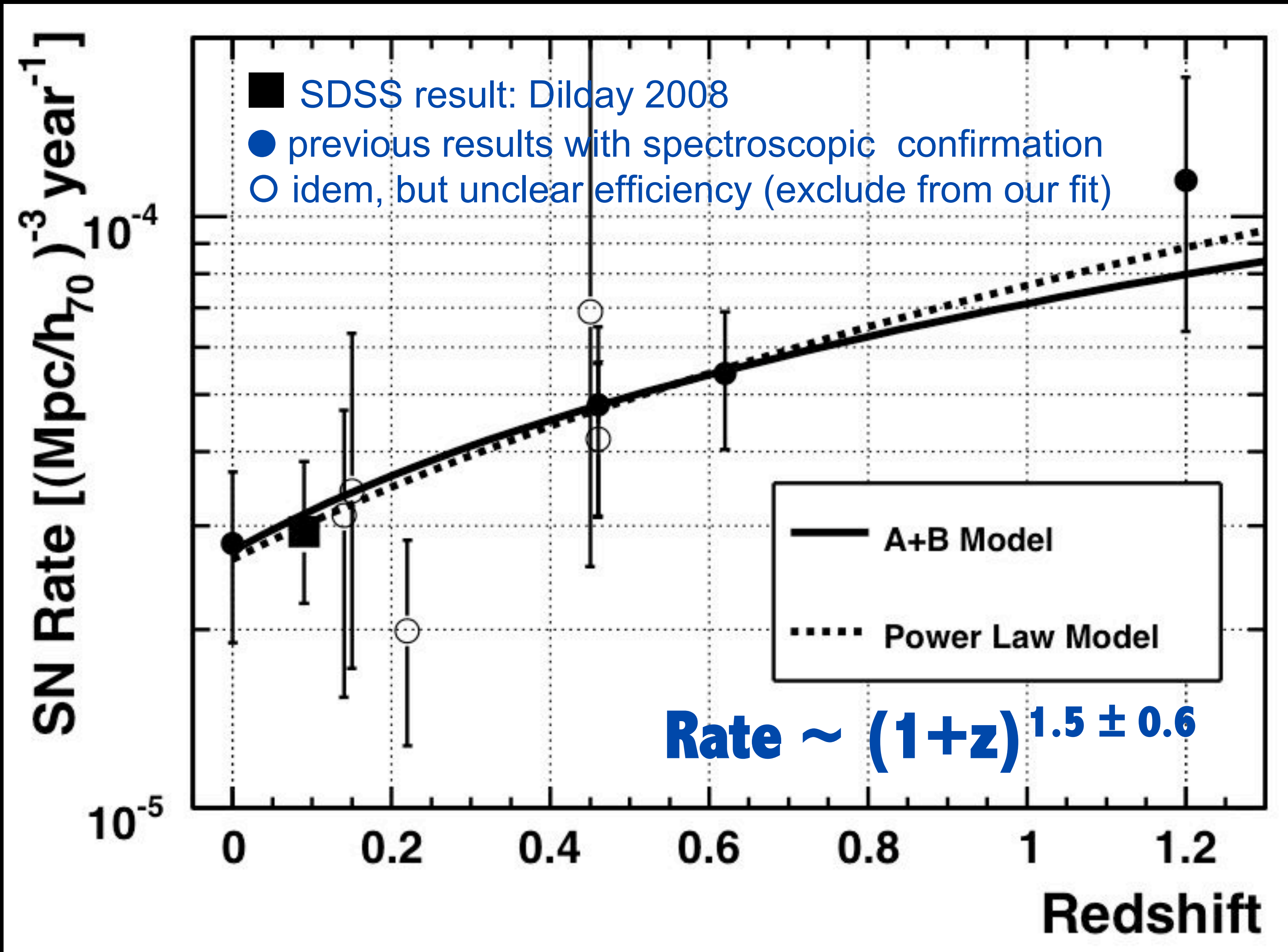


Contributions:

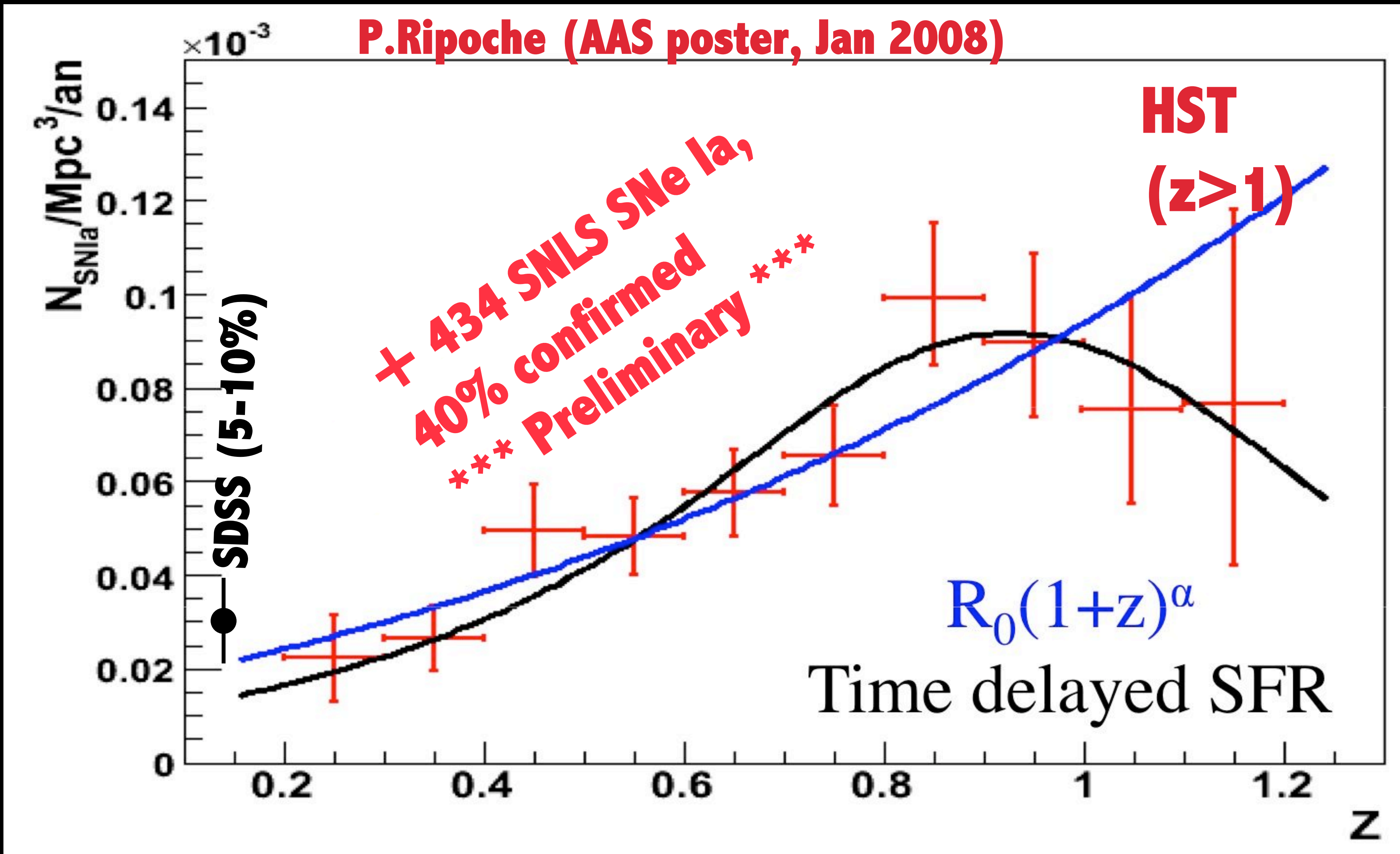
16 spectroscopically confirmed Ia (26 before cuts)

1 photometric-id with host spec-Z

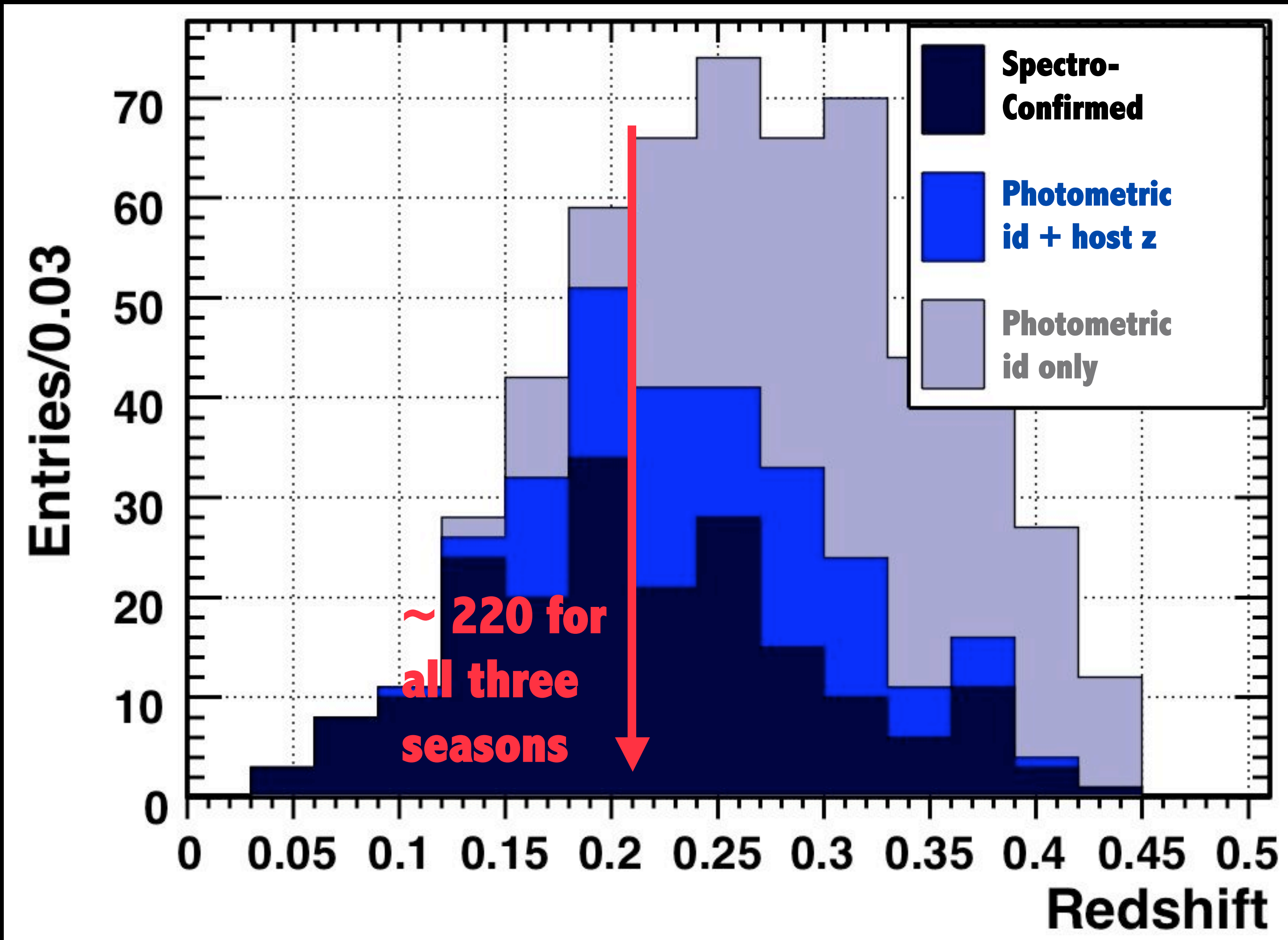
Unbinned Likelihood Fit



Rate vs. Redshift

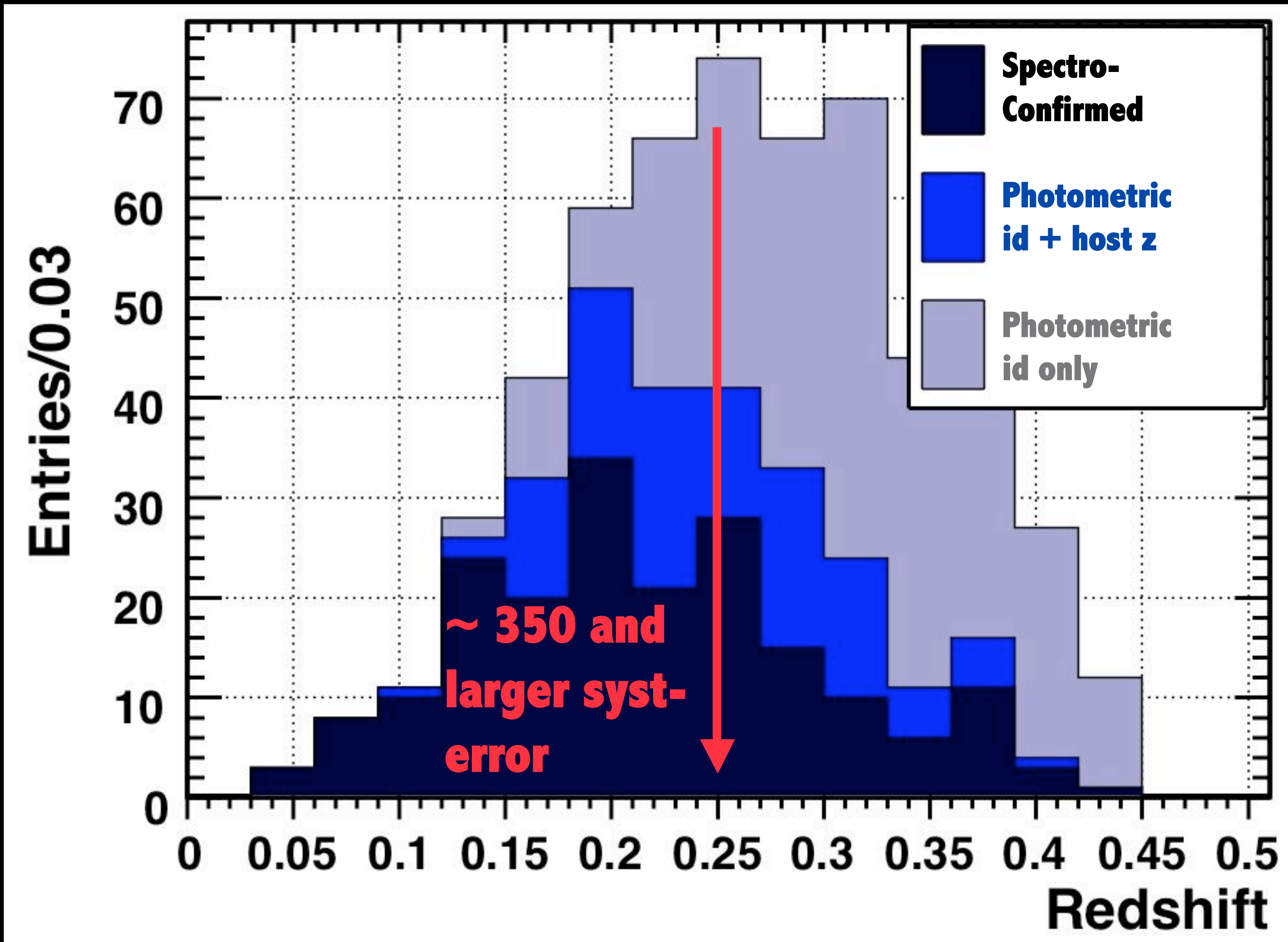


SDSS SN Ia Rate: in progress



statistics
vs.
systematics

SDSS SN Ia Rate: in progress

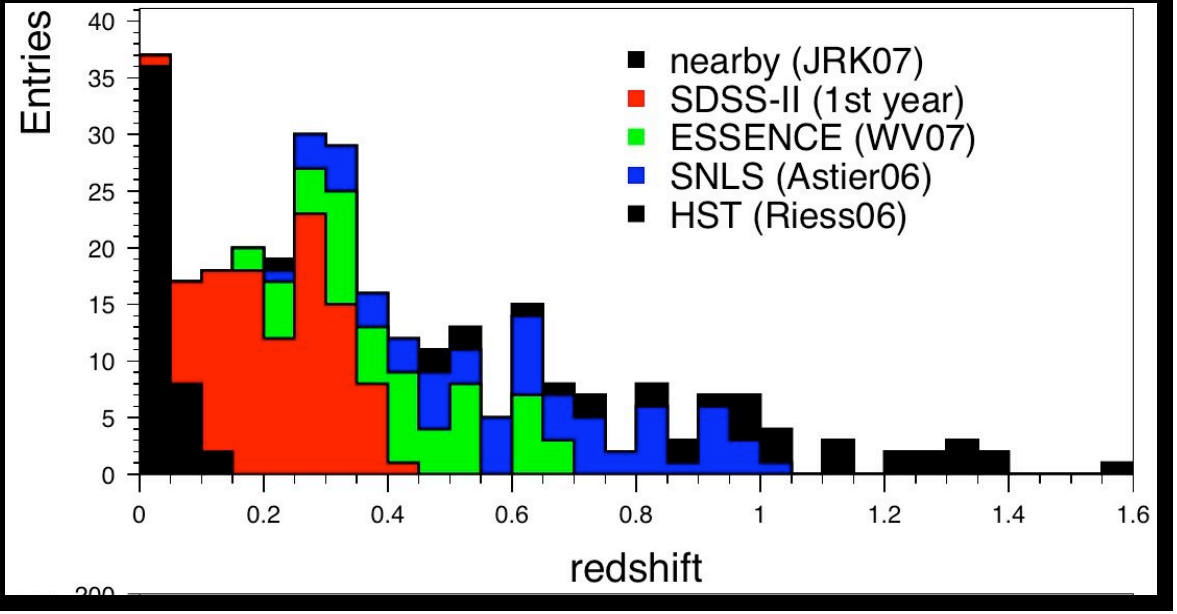


statistics
vs.
systematics

SDSS-II Hubble Diagram Analysis: Samples Include

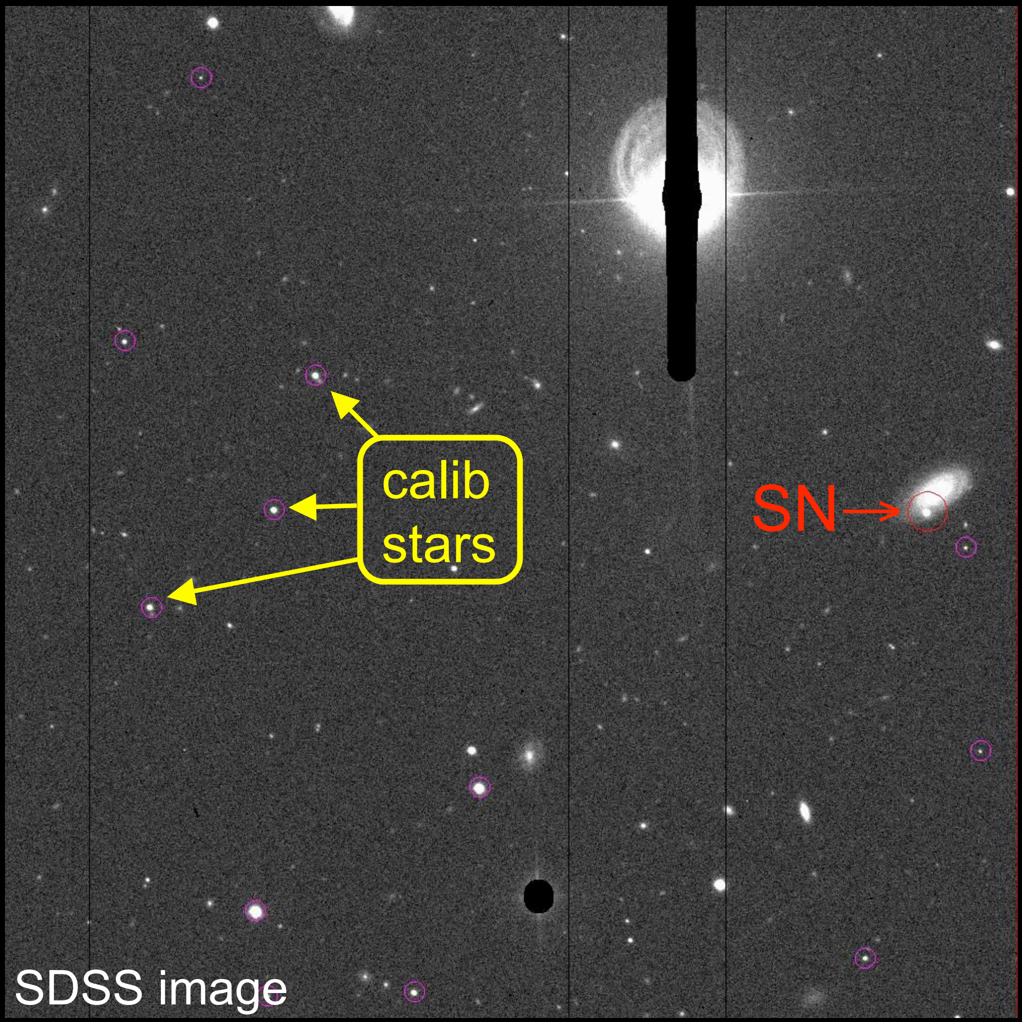
- SDSS, Fall-2005 (103)
- Low redshift from literature (33)
- SNLS published (~ 70)
- ESSENCE published (~ 60)
- HST (34)

Paper to be submitted soon to ApJ …



Supernova Photometry from Fit

(Holtzman et. al., 2008, accepted by ApJ)



FIT-DATA:
all images (few dozen × ugriz)

FIT-MODEL:
galaxy + stars + SN + sky

FIT PROPERTIES:
gal + stars: same in every image
SN: variable in every image
gal + stars + SN: PSF-smeared

NO PIXEL RE-SAMPLING !
➪ no pixel correlations
➪ proper stat. errors

Extensive Photometry Tests Include:

- Recover zero flux pre-explosion
- Recover star mags
- Recover flux from fake SN

Analysis Overview

- Use both MLCS2k2 & SALT2 methods without retraining ==>

  use essentially as-is

- Make necessary & obvious improvements to implementation, but not to underlying method.

- Identify problems & evaluate systematic uncertainties.

Analysis Overview

- Six sample-combinations

  a) SDSS-only

  b) SDSS + ESSENCE + SNLS

  c) Nearby + SDSS

  d) Nearby + SDSS + ESSENCE + SNLS

  e) Nearby + SDSS + ESSENCE + SNLS +HST

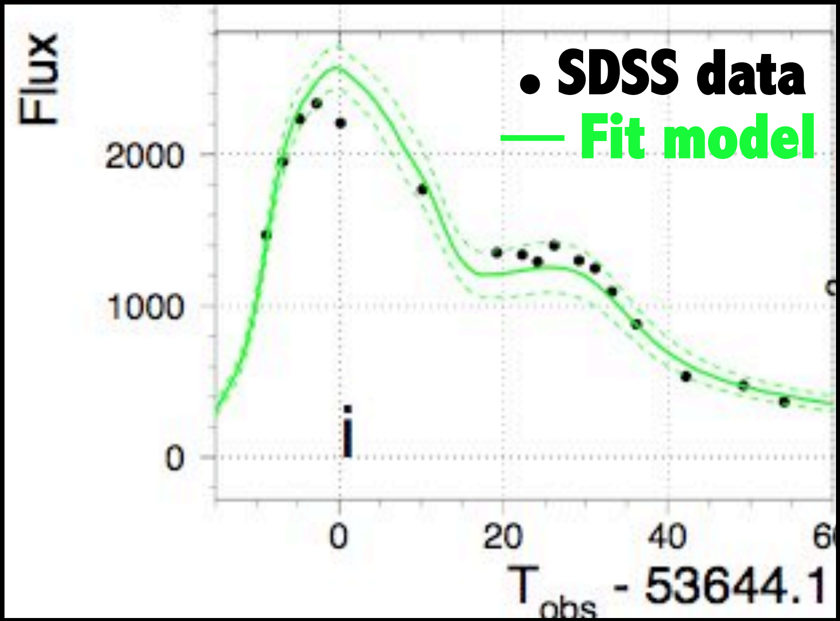
  f) Nearby + ESSENCE + SNLS **(compare to WV07)**

no nearby sample; SDSS is lowz anchor

SDSS is high-z sample

Lightcurve Fit: Brief Reminder

- Fit data to parametric model (or template) to get shape and color.
- Use shape and color to "standardize" intrinsic luminosity.



Lightcurve Fit: Brief Reminder

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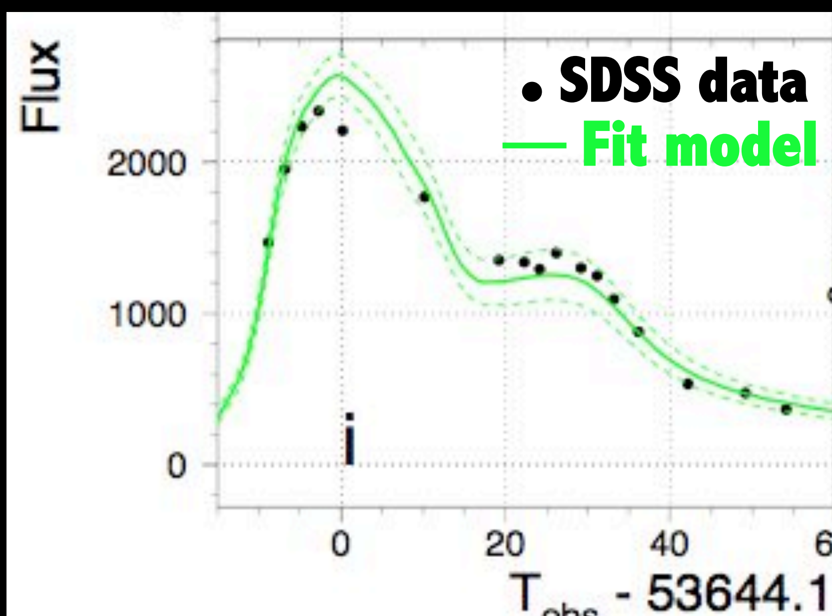


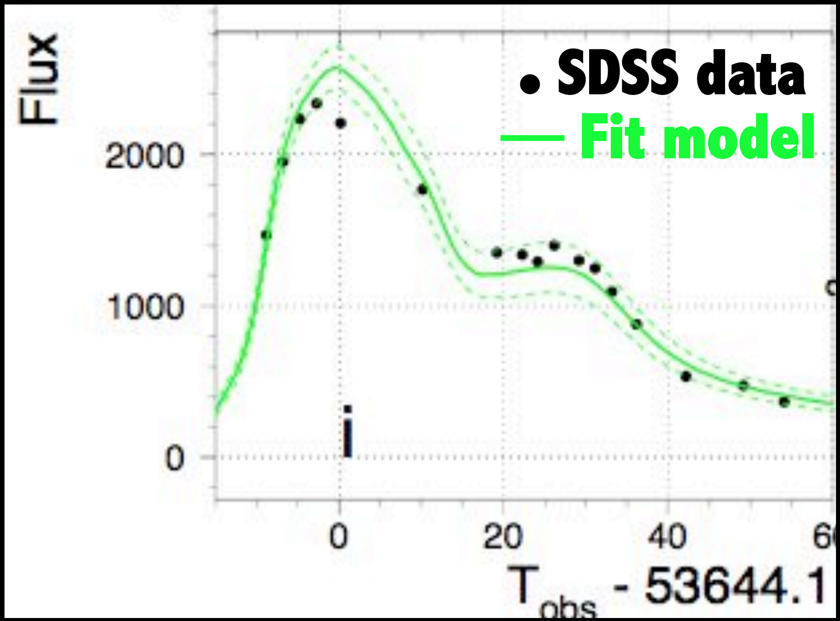
Jargon:

"SN Training"

is the procedure for determining the relation between shape+color and intrinsic luminosity

Lightcurve Fit: Brief Reminder

- Fit data to parametric model (or template) to get shape and color.
- Use shape and color to "standardize" intrinsic luminosity.



Distance-modulus (μ) =
Observed mag –
Intrinsic mag

Lightcurve Fit: Brief Reminder

- Fit data to parametric model (or template) to get shape and color.
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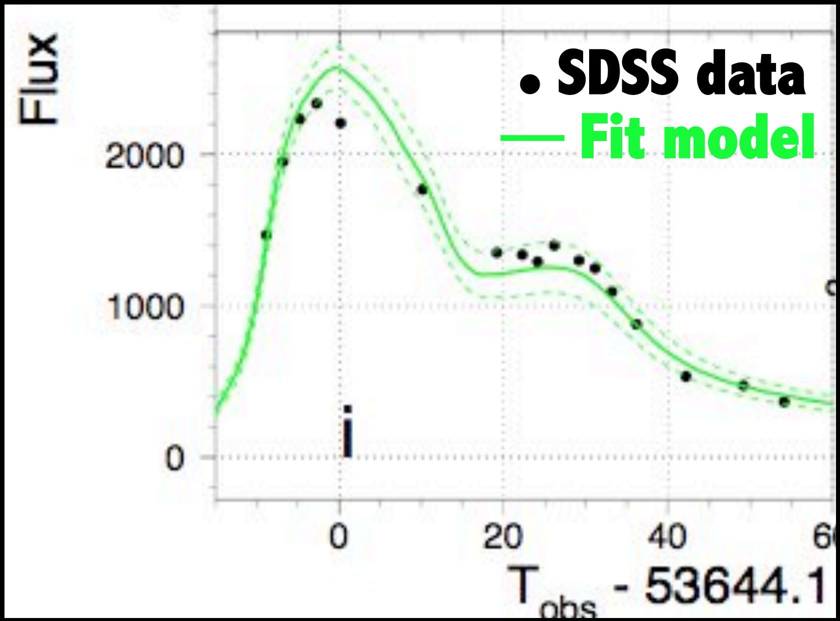
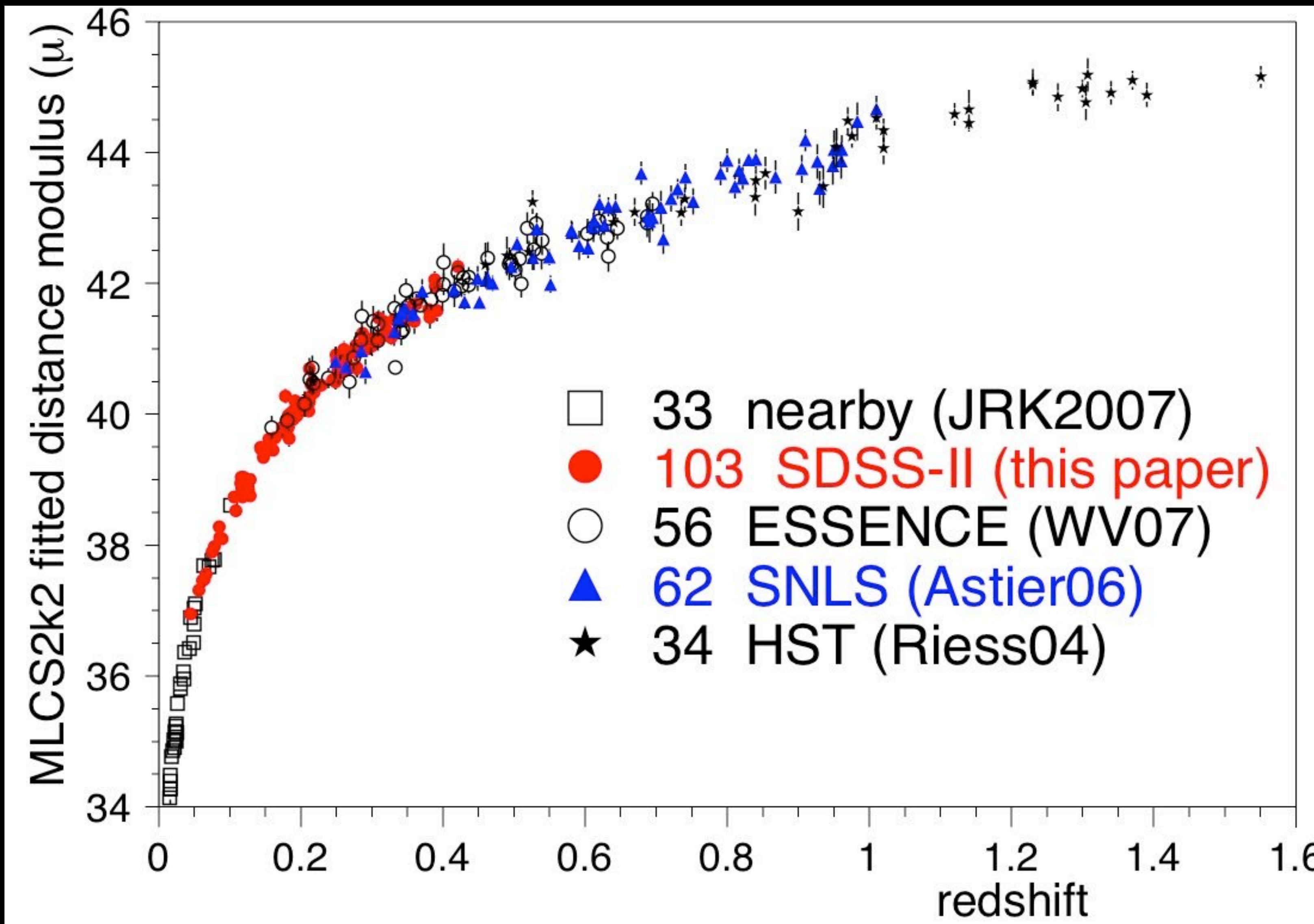
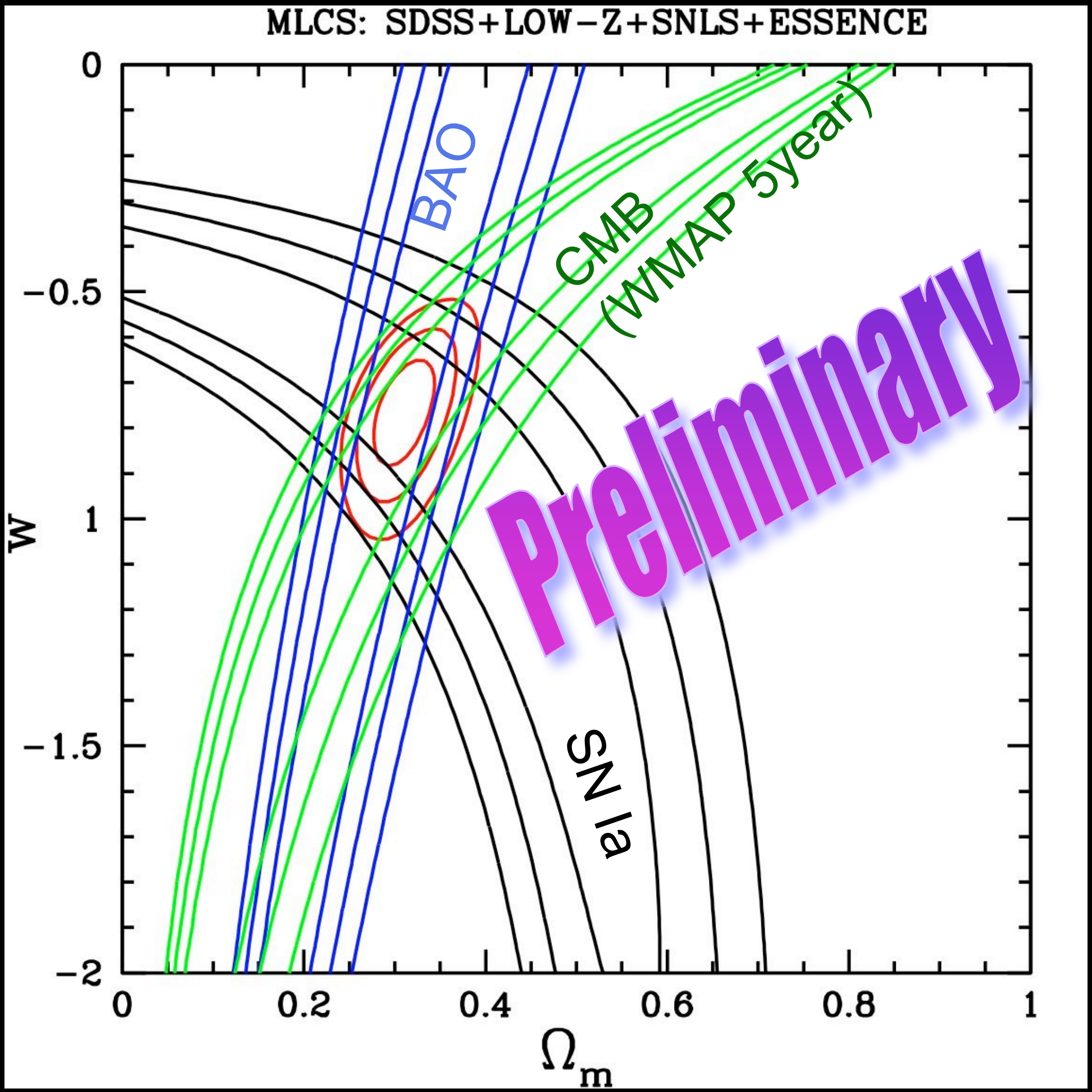


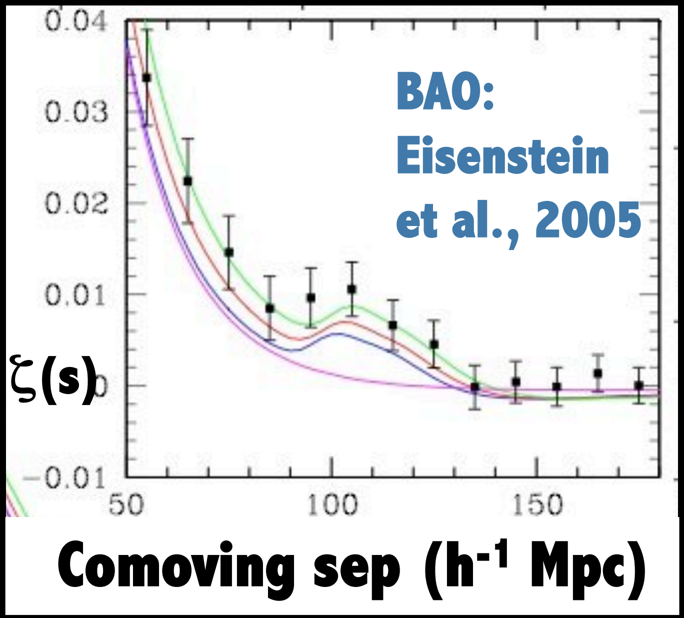
Distance-modulus (μ) =
Observed mag –
Intrinsic mag –
Dust-Extinction(??)

SN Ia Hubble Diagram



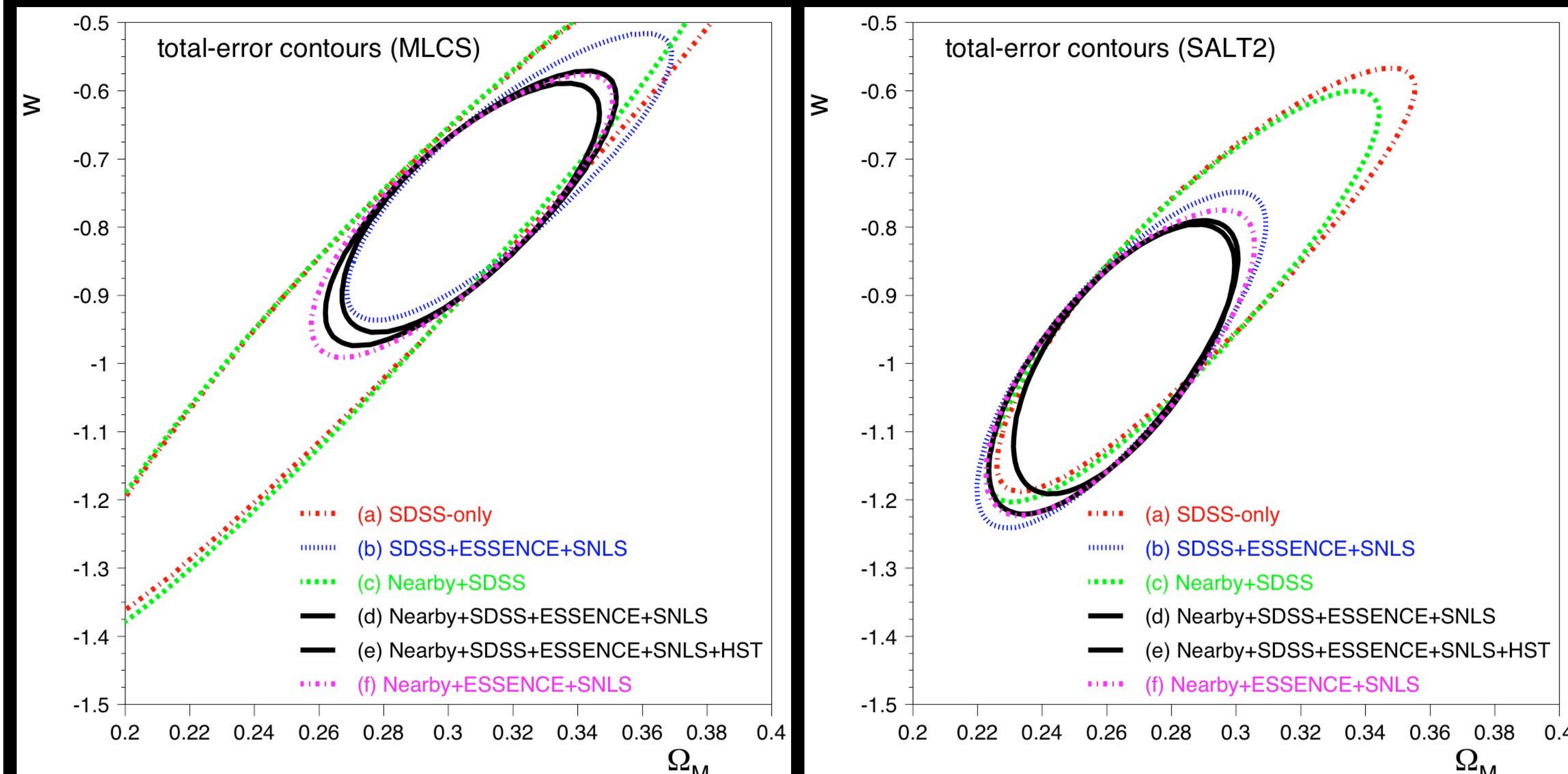
Cosmology Fit for w and Ω_M using SN+BAO+CMB





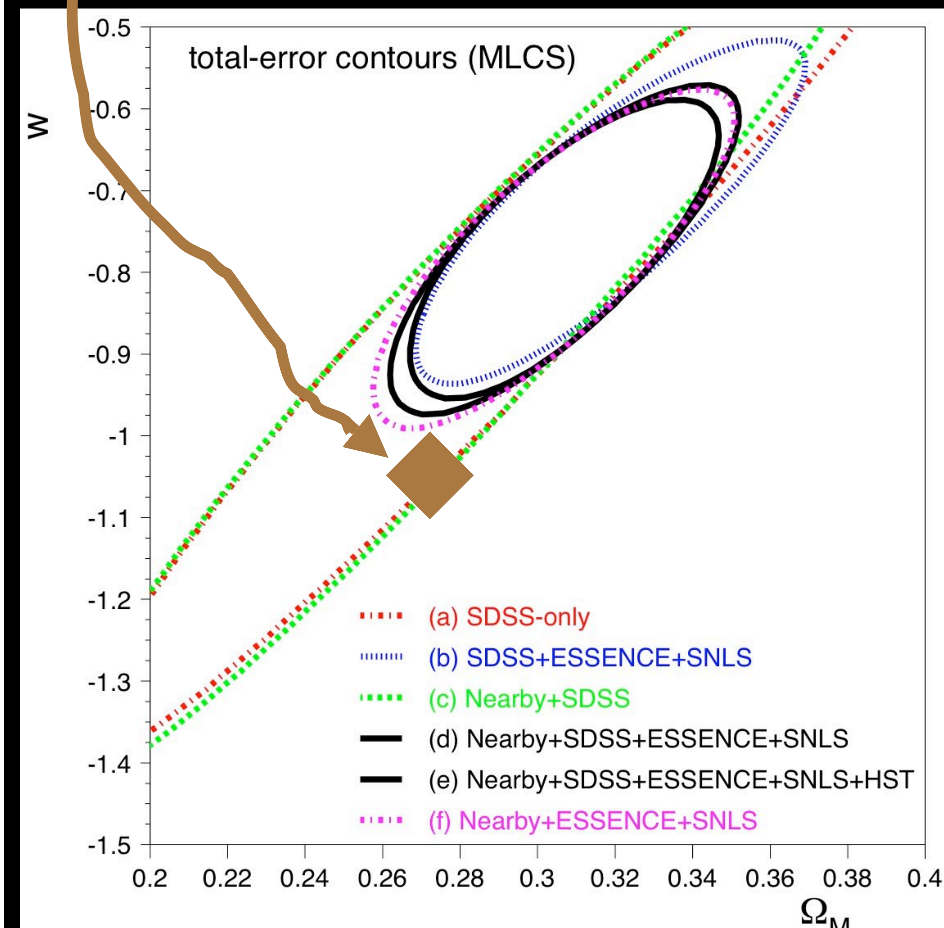
Preliminary

Results



Results

ESSENCE: Wood-Vasey, AJ 666, 694 (2007)
SNLS: Astier, AJ 447, 31 (2006)



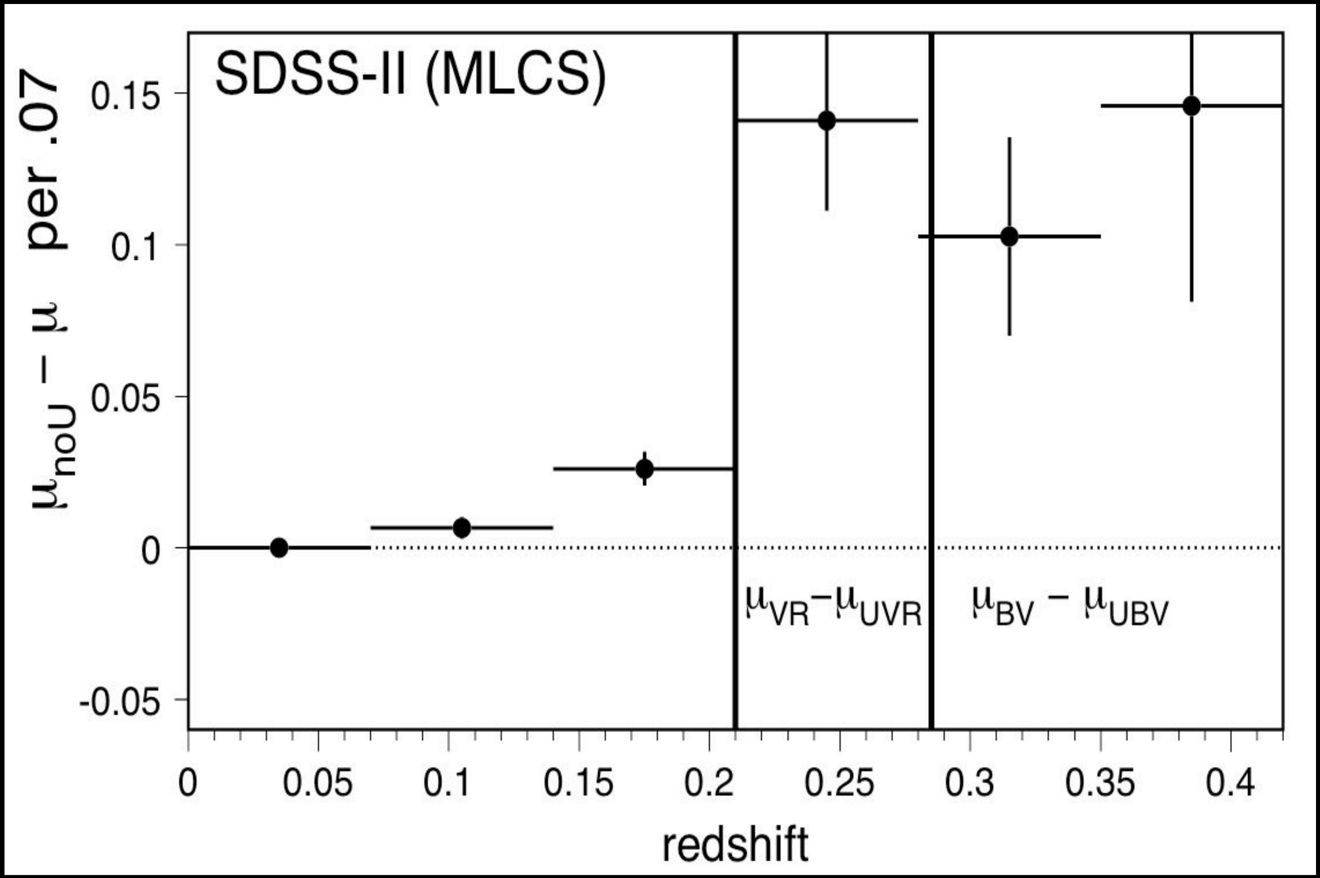
Questions to Ponder

Q1: Why is SDSS-only systematic error so large ?

Q2: Why does our MLCS-based *w*-result differ by ~ 0.3 compared to WV07 (same method & same data) ?

Q3: Why do MLCS and SALT2 results differ when high-redshift samples (ESSENCE + SNLS) are included ?

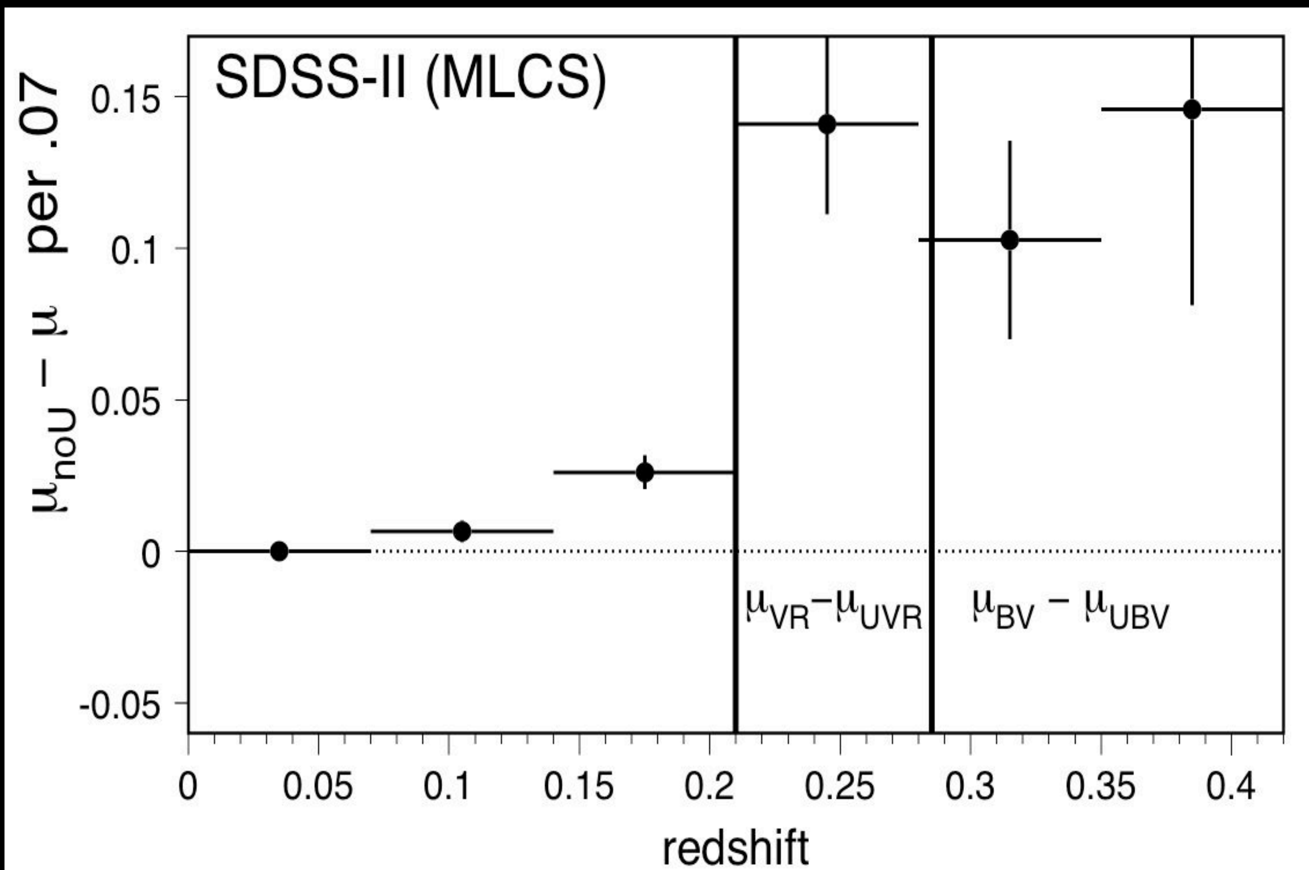
Q1: Why is SDSS-only Systematic Error so Large ?

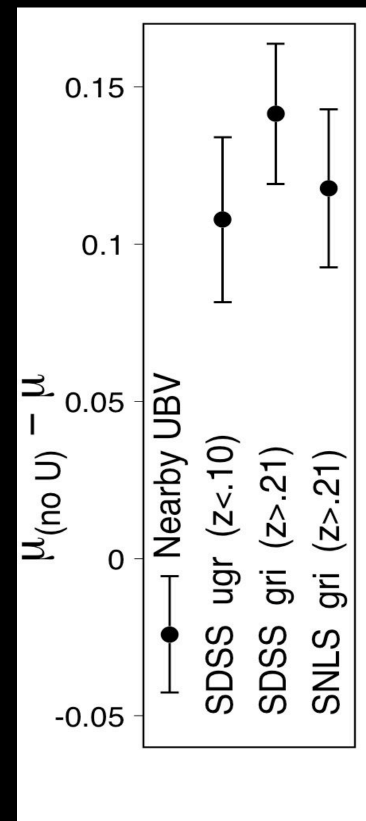


$\sigma_w(\text{syst}) = .3$

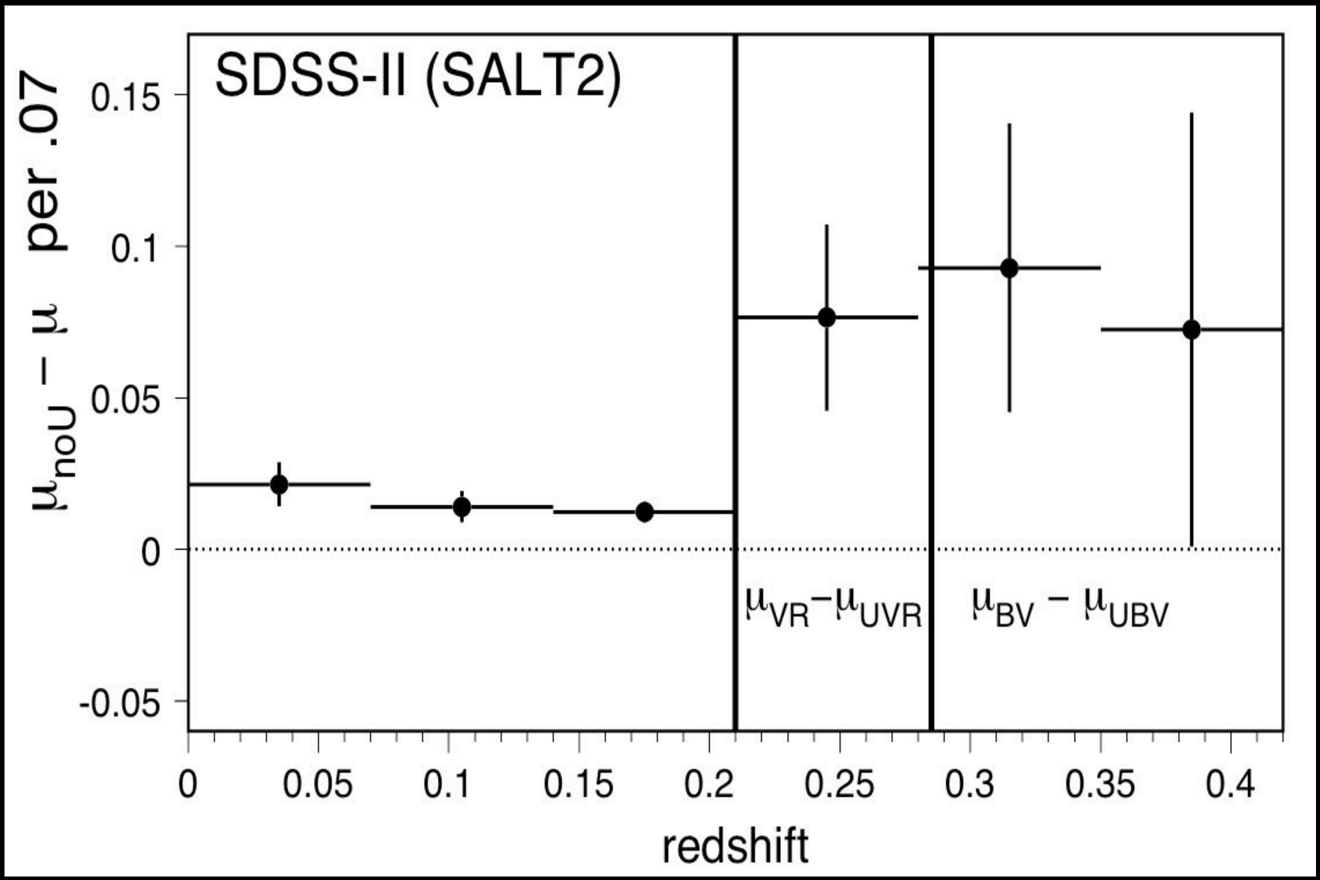
$= 2\times\sigma_w(\text{stat})$

Q1: Why is SDSS-only Systematic Error so Large ?





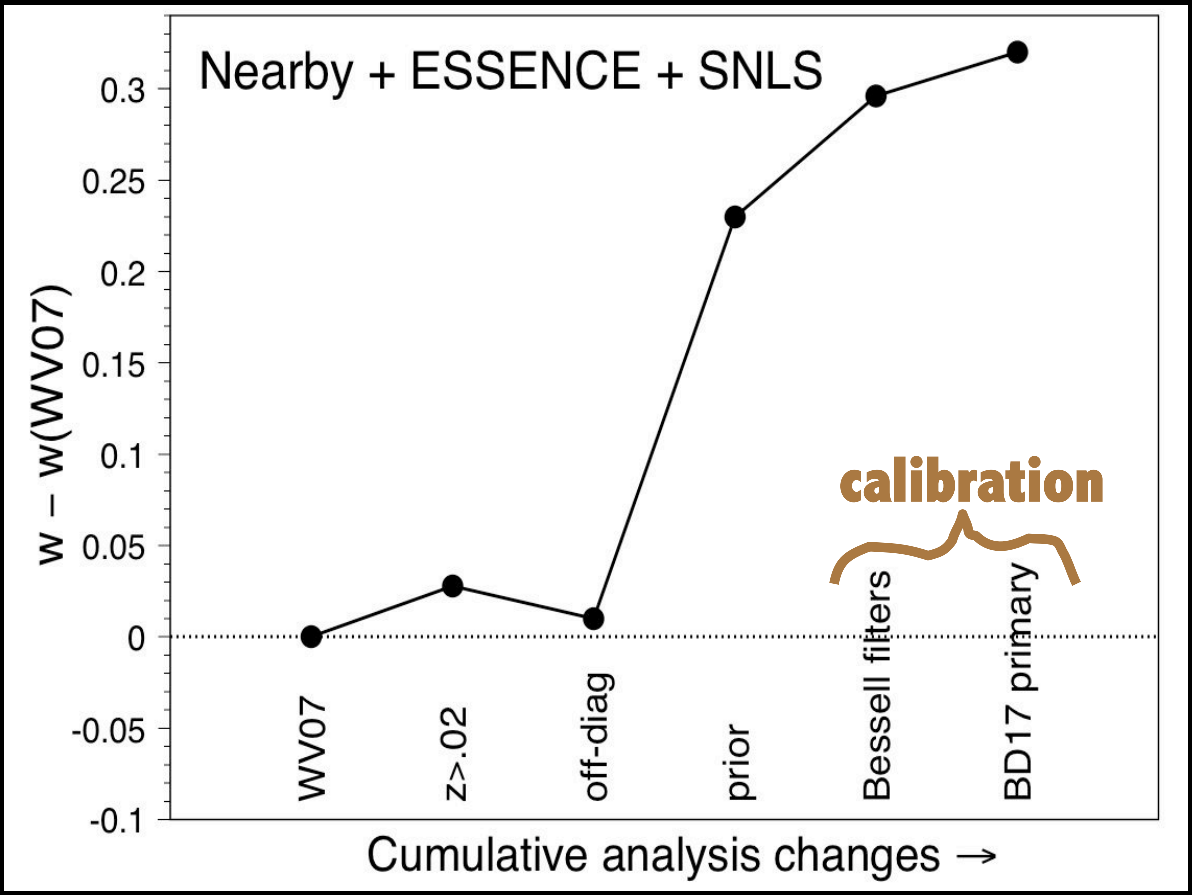
Q1: Why is SDSS-only Systematic Error so Large ?



Global SALT2 "minimization" dampens U-bias:

$$\sigma_w(\text{syst}) = .15$$

Q2: Why does our MLCS-based w-result differ by ~ 0.3 compared to WV07 (same method & same data) ?



***Prior* :**

survey efficiencies

&

host-galaxy dust

Comments on MLCS Fit Prior

- Prior ‘P’ = (underlying extinction distribution) x (observation efficiency): P=0 when $A_V < 0$
- $\chi^2 \rightarrow \chi^2 - 2\ln P$ (in light curve fit)
- Equivalent to using flat prior, and then applying bias-correction on each fitted distance modulus
- Either method (above) requires detailed simulation and knowledge of dust properties.

Spectroscopic Inefficiency

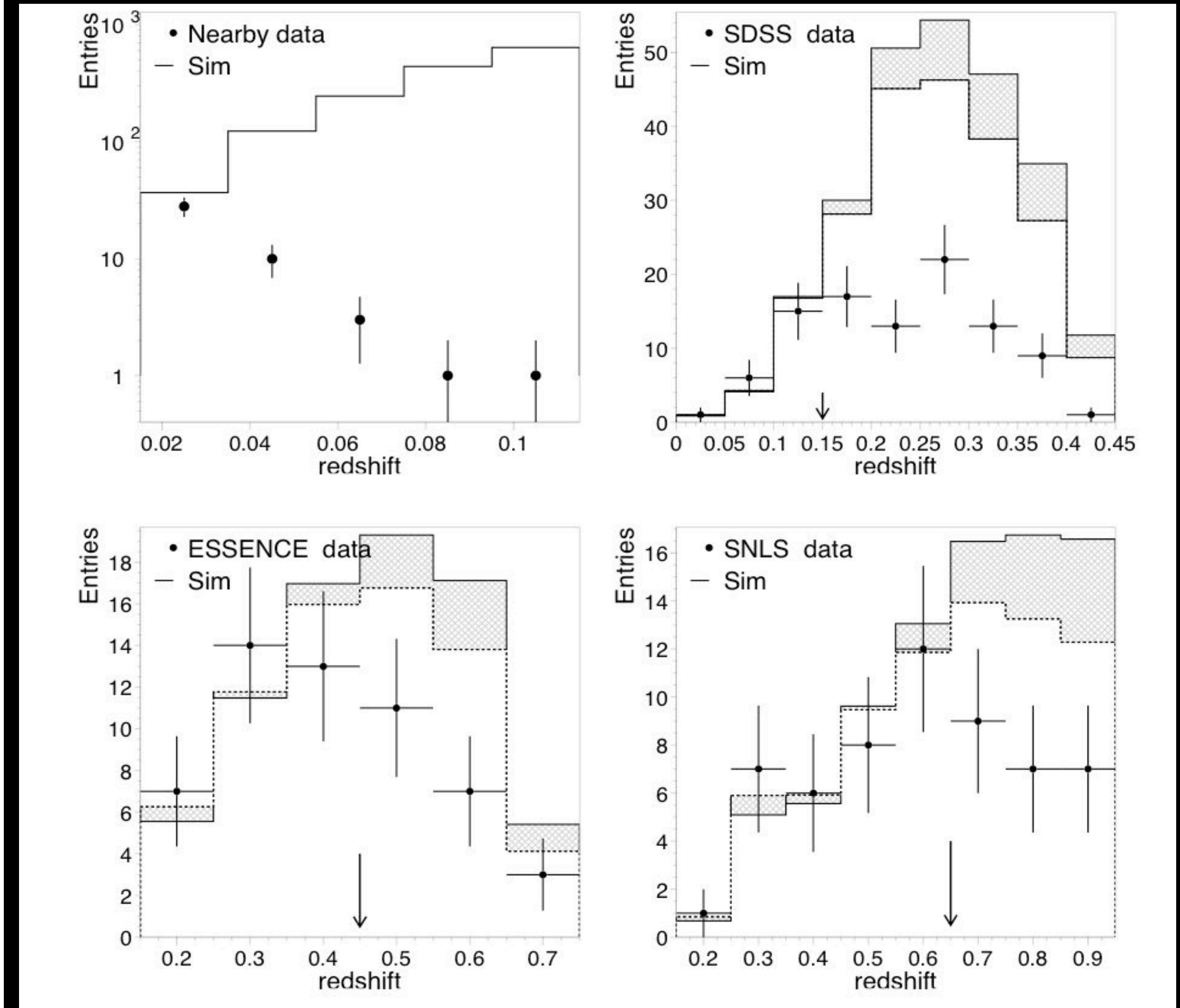


Fig. 8.— Comparison of redshift distributions for data (dots) and simulations (histograms) for the four SN samples: nearby (Jha et al. 2007), SDSS-II (2005 sample), ESSENCE (Wood-Vasey et al. 2007), and SNLS (Astier et al. 2006). The nearby sample is shown on a loga-

- **Simulate all known effects using REAL observing conditions**
- **Compare data/sim redshift distributions**
- **Difference attributed to spectroscopic ineff.**

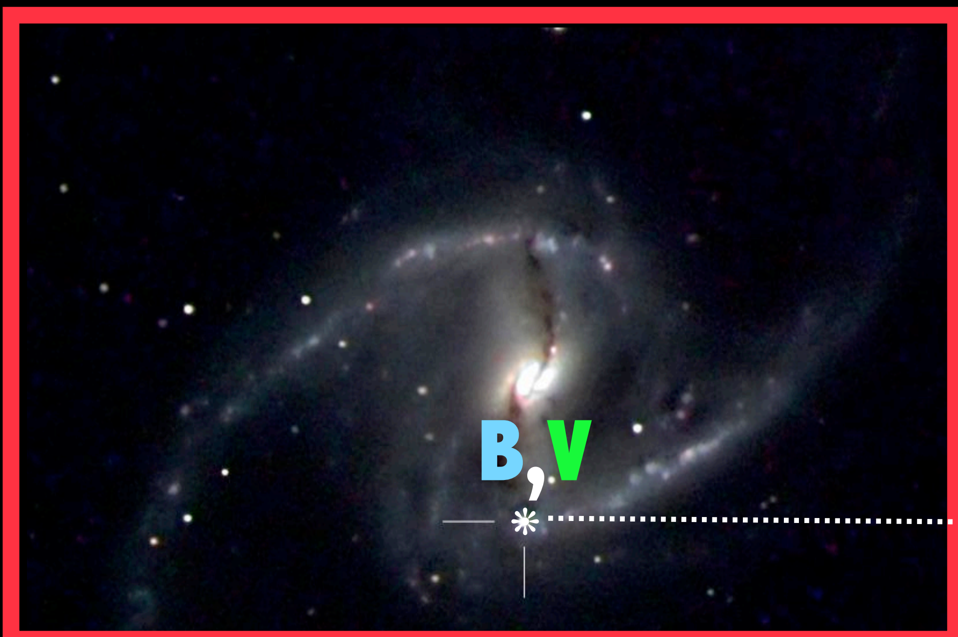
Spectroscopic Inefficiency
(ignored in WV07)

- ☆ Spectroscopic efficiency modeled as $\exp(-m_V/\tau)$
- ☆ Eff(spec) is included in fitting prior …
- ☆ SDSS-only w-shift is 0.13 ;
  much smaller w-shifts for sample-combinations
- ☆ Assign w-syst error = 1/2 change from this effect

Dust Law: $R_V = A_V/E(B–V)$ and $A(\lambda)$ from

Cardelli, Clayton, Mathis ApJ, 345, 245 (1989)

Blue light scatters more → extincted objects appear redenned.



$B+\Delta B$, $V+\Delta V$

earth

$$E(B - V) = \Delta B - \Delta V$$

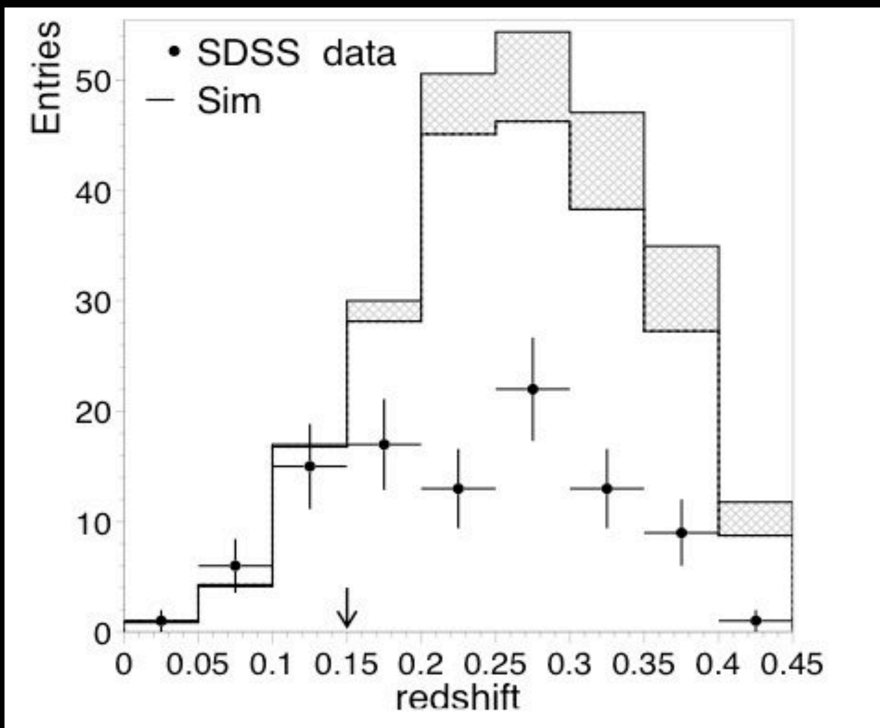
Dust Law: $R_V = A_V/E(B\text{–}V)$ and $A(\lambda)$ from

Cardelli, Clayton, Mathis ApJ, 345, 245 (1989)

- Previous MLCS-based analyses assumed $R_V = 3.1$ (global parameter)
- Growing evidence points to $R_V \sim 2$:
  - ➔ SALT2 "β" $(R_V+1) = 2 - 2.5$
  - ➔ LOWZ studies (Nobili 08: $R_V = 1.8$)
  - ➔ individual SN with NIR (Krisciunas)
- We have evaluated R_V with our own SDSS-II data

Dust Law: $R_V = A_V/E(B–V)$

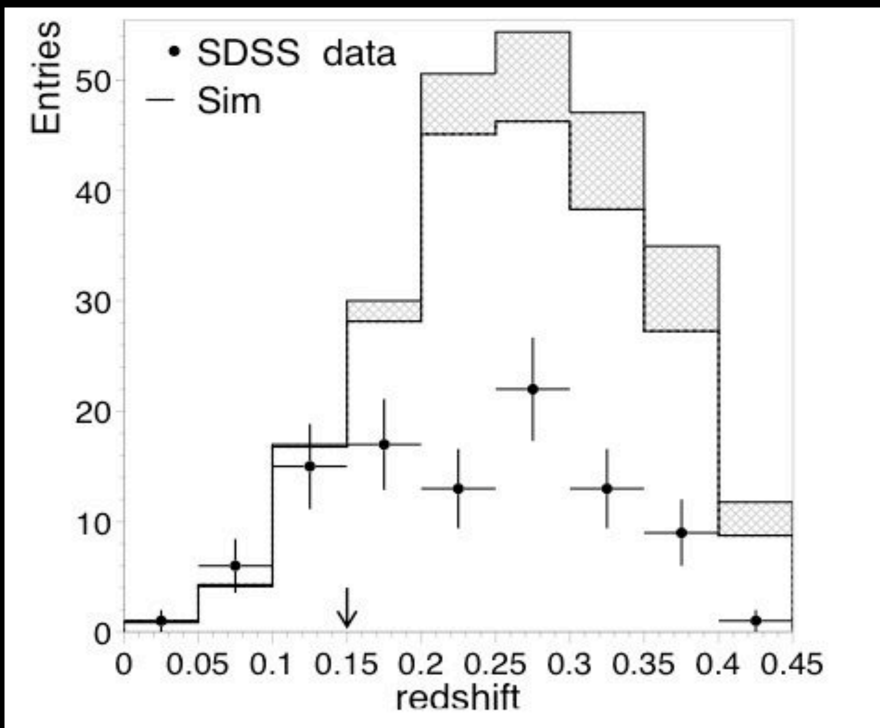
To measure a global property of SN Ia, need sample with well-understood efficiency



Spec-confirmed SN Ia sample has large (spec) inefficiency that is not modeled by the sim.

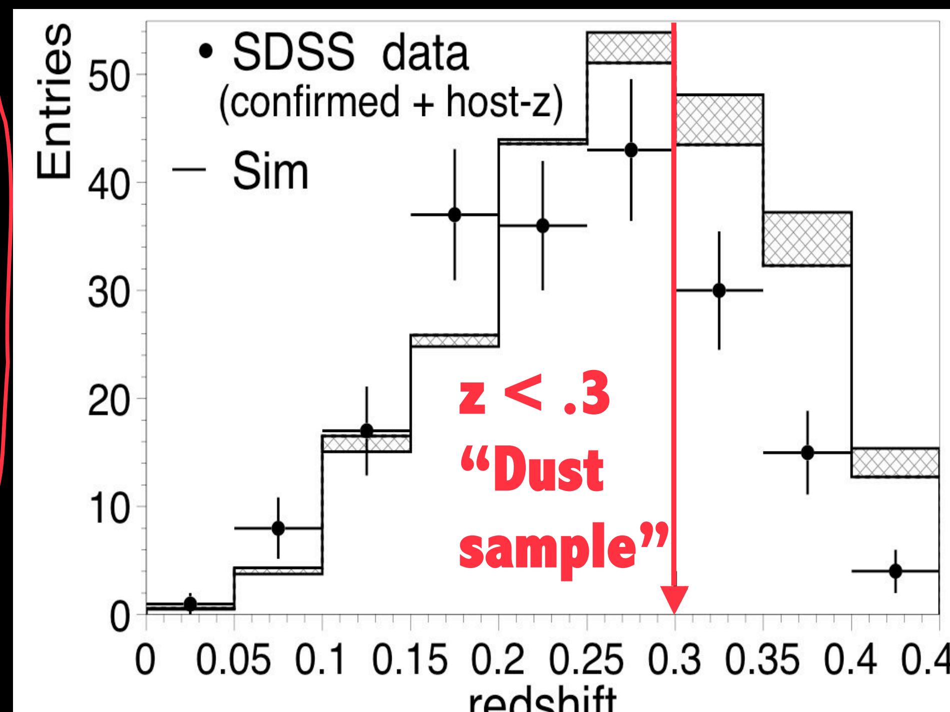
Dust Law: $R_V = A_V/E(B-V)$

To measure a global property of SN Ia, need sample with well-understood efficiency



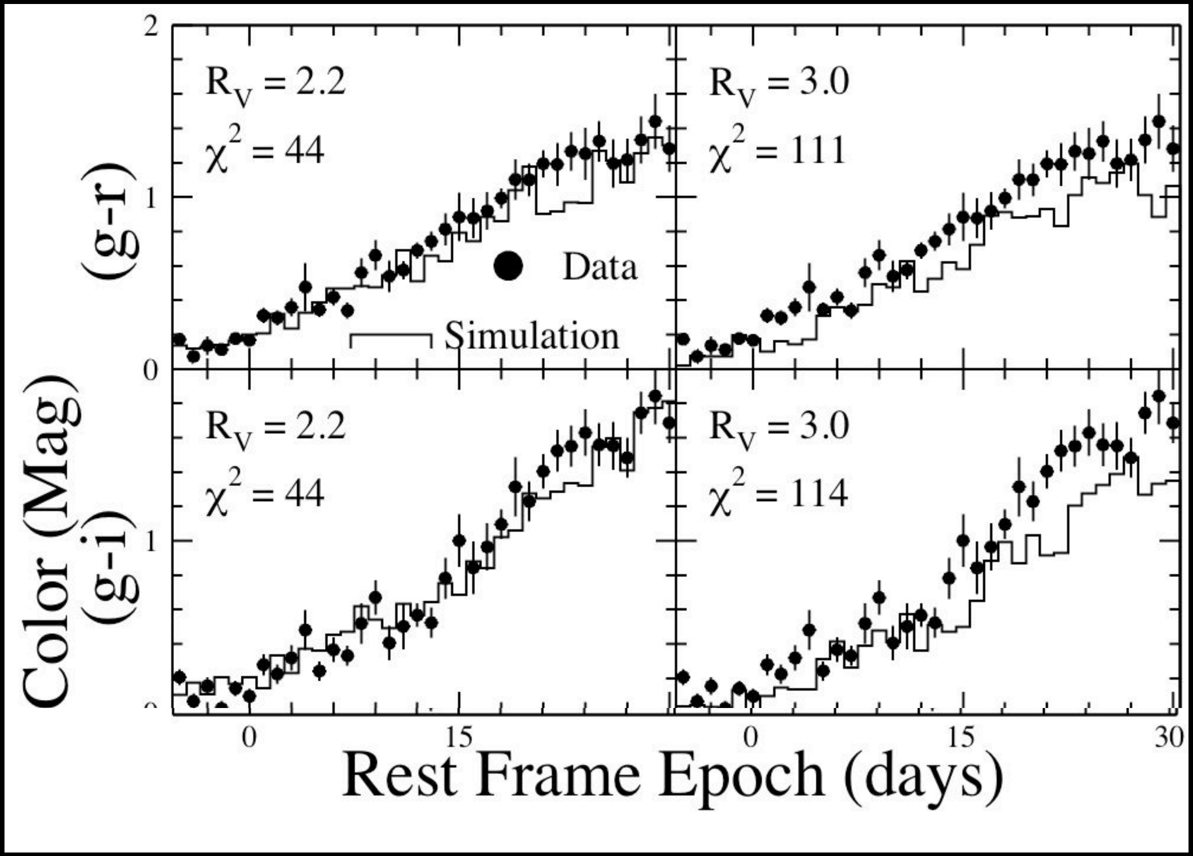
Spec-confirmed SN Ia sample has large (spec) inefficiency that is not modeled by the sim.

Solution: include photometric SNe Ia with host-galaxy redshift !



Dust Law: $R_V = A_V/E(B–V)$

Method: minimize data-MC chi2 for color vs. epoch



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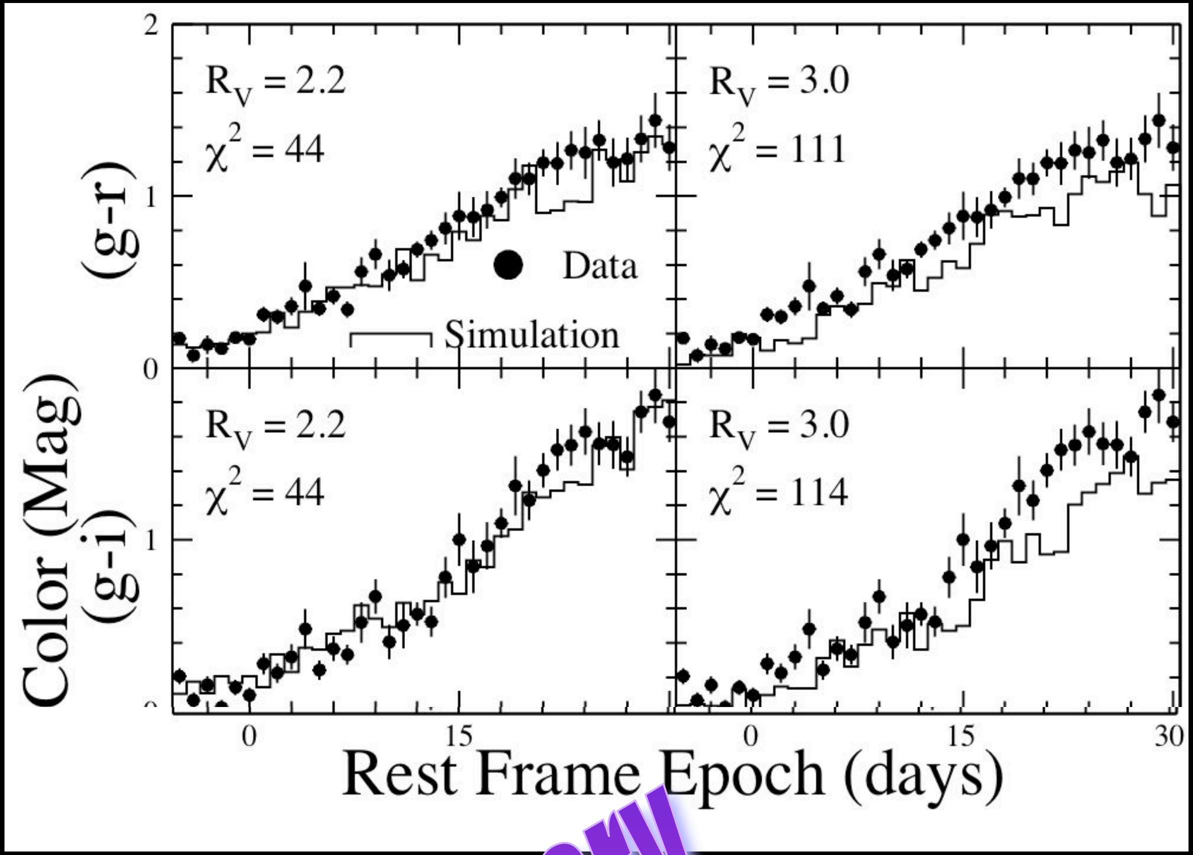

SDSS Result:

$R_V = 2.23 \pm 0.14_{stat} \pm 0.45_{syst}$

Consistent with SALT2 β and other SN-based studies.

Preliminary

Q2: Why does our MLCS-based w-result differ by ~ 0.3 compared to WV07 (same method & same data) ?

- ☆ R_V = 2.2 (instead of 3.1 in WV07)
- ☆ Account for spectroscopic inefficiency (ignored in WV07)

… and not discussed in this talk:

- ☆ different A_V distribution than in WV07
- ☆ Different treatment of Bessell filters for nearby (z < 0.1) sample
- ☆ Fit in flux instead of mag (avoids bias from removing SNR<5 measurements)

Q3: SALT2-MLCS Discrepancy: $\delta w \sim 0.2$?

Oh no, these two light curve fitters give inconsistent values for w !

Comparison of Lightcurve Fit Methods

property	MLCS2k2 (Jha 2007)	SALT2/SNLS (Guy07)
rest-frame model	U,B,V,R,I mag vs. t	spectral surface vs. t
color variations	host-galaxy dust	dust + intrinsic (no assump)
Fitting prior	Extinction $A_V > 0$	none

Comparison of Lightcurve Fit Methods

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K-correction	warp composite SN Ia spectrum from Hsiao	not needed
distance modulus	Fit-param for each SN Ia	from global fit

Comparison of Lightcurve Fit Methods

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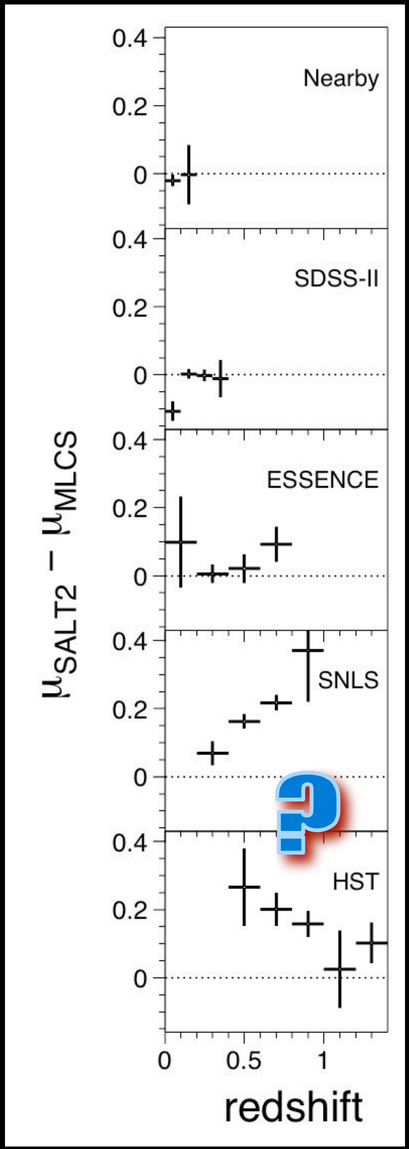
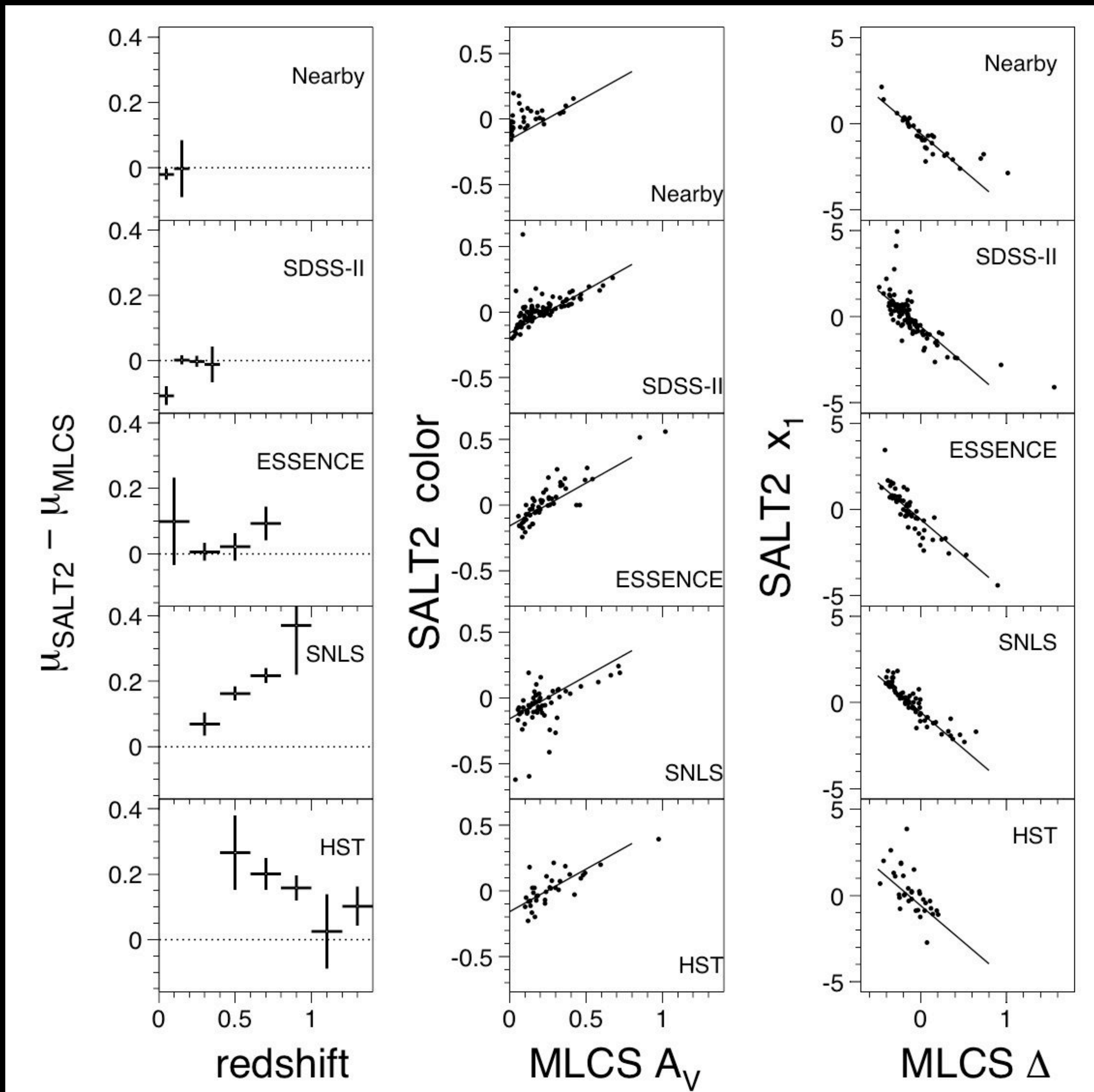
Fitting prior	Extinction $A_V > 0$	none
K-correction	warp composite SN Ia spectrum from Hsiao	not needed
distance modulus	Fit-param for each SN Ia	from global fit
Training	z < .1 : SN lum & shape SDSS: R_V, A_V	all SNe used in training
Fitter availability	wrote our own fitter with improvements & options	black box provided by J.Guy of SNLS
Training availability	requires highly trained chef	Turn-key code, but crucial SNLS spectra are private

MLCS-SALT2 Comparisons



MLCS-SALT2 Comparisons



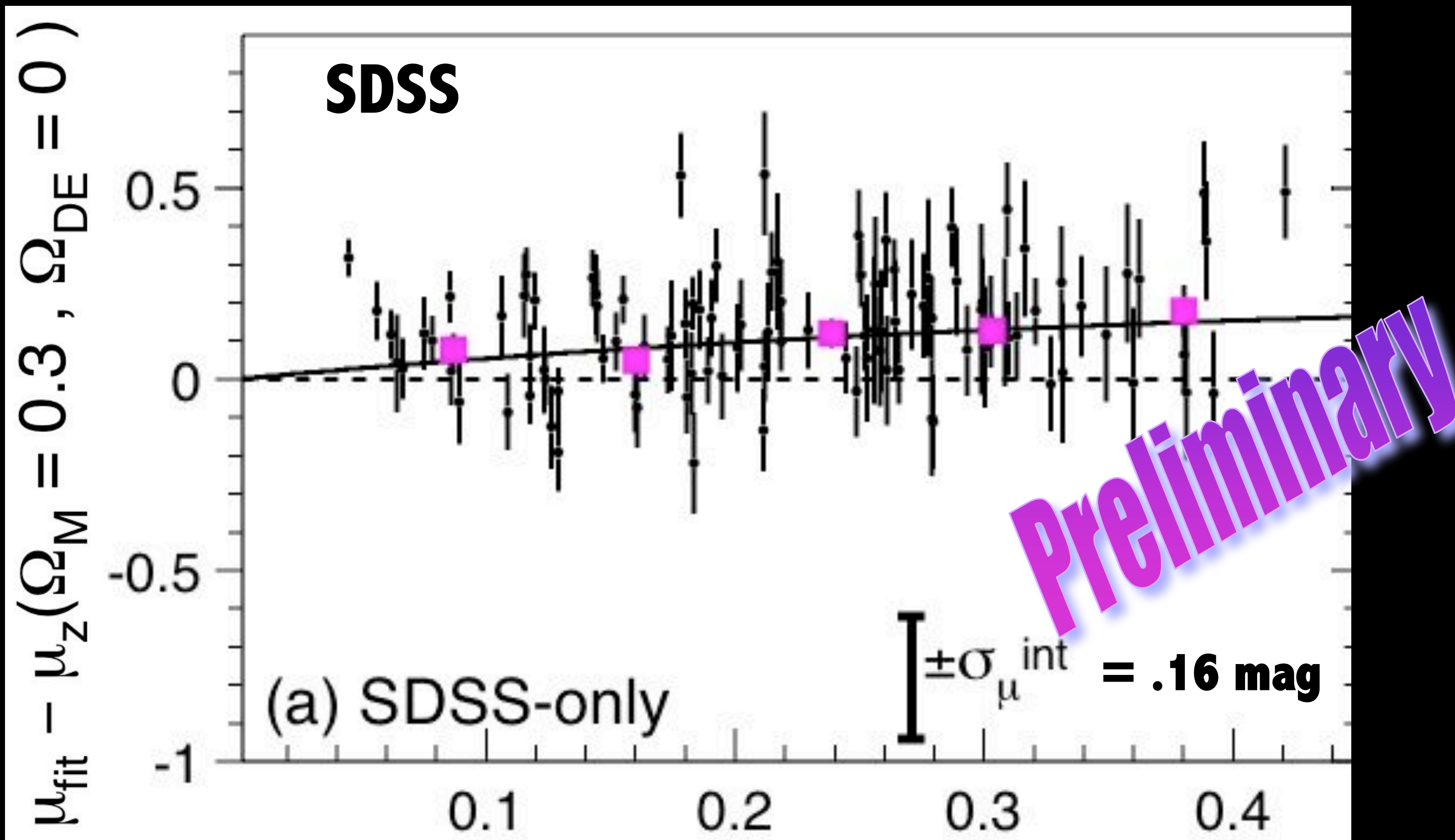
Summary

- ☆ SN-cosmology analysis with first-season SDSS-II sample (103 SNe Ia) is complete; paper near completion.
- ☆ w-measurements are systematics-limited.
- ☆ Found lots of issues and problems to address using SDSS-SN for retraining & analysis with full 3-year sample.
- ☆ Ideas welcome !!!

- ☆ Warning/complaint: we really need turn-key training codes to study discrepancies & systematic uncertainties.

Extra Slides

Fit Residuals



redshift

Fit Residuals

Table 13: Hubble diagram fit-quality parameters for each sub-sample.

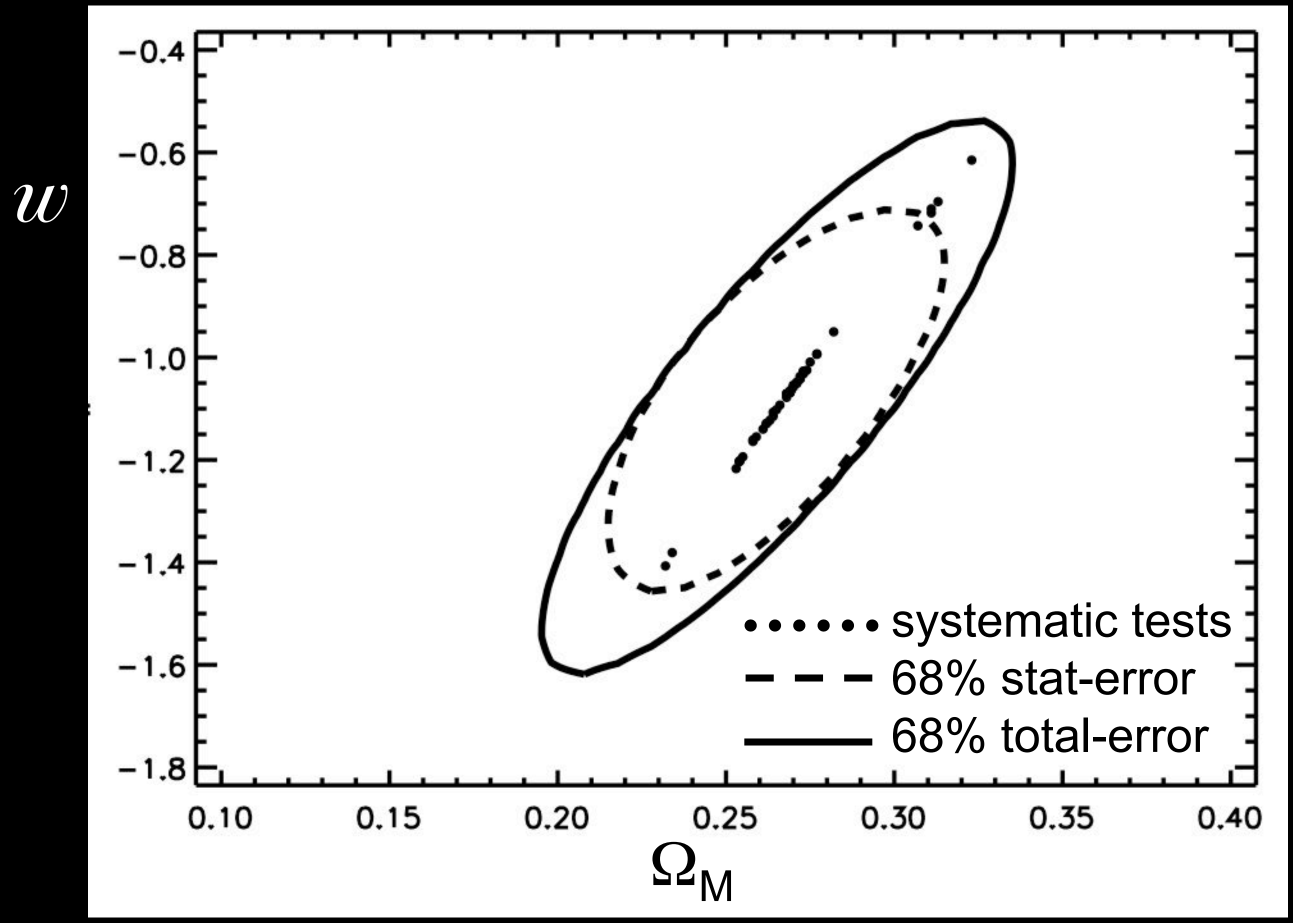
fit-quality parameter	Result for sample: Nearby	SDSS-II	ESSENCE	SNLS	HST
χ^2_μ (independent fits)	31.2	53.6	49.6	59.3	33.4
N_{dof}	30	100	53	59	31
RMS_μ	0.19	0.14	0.23	0.23	0.27

?

Preliminary

smaller χ^2 is due to inefficiency from spectroscopic targeting.

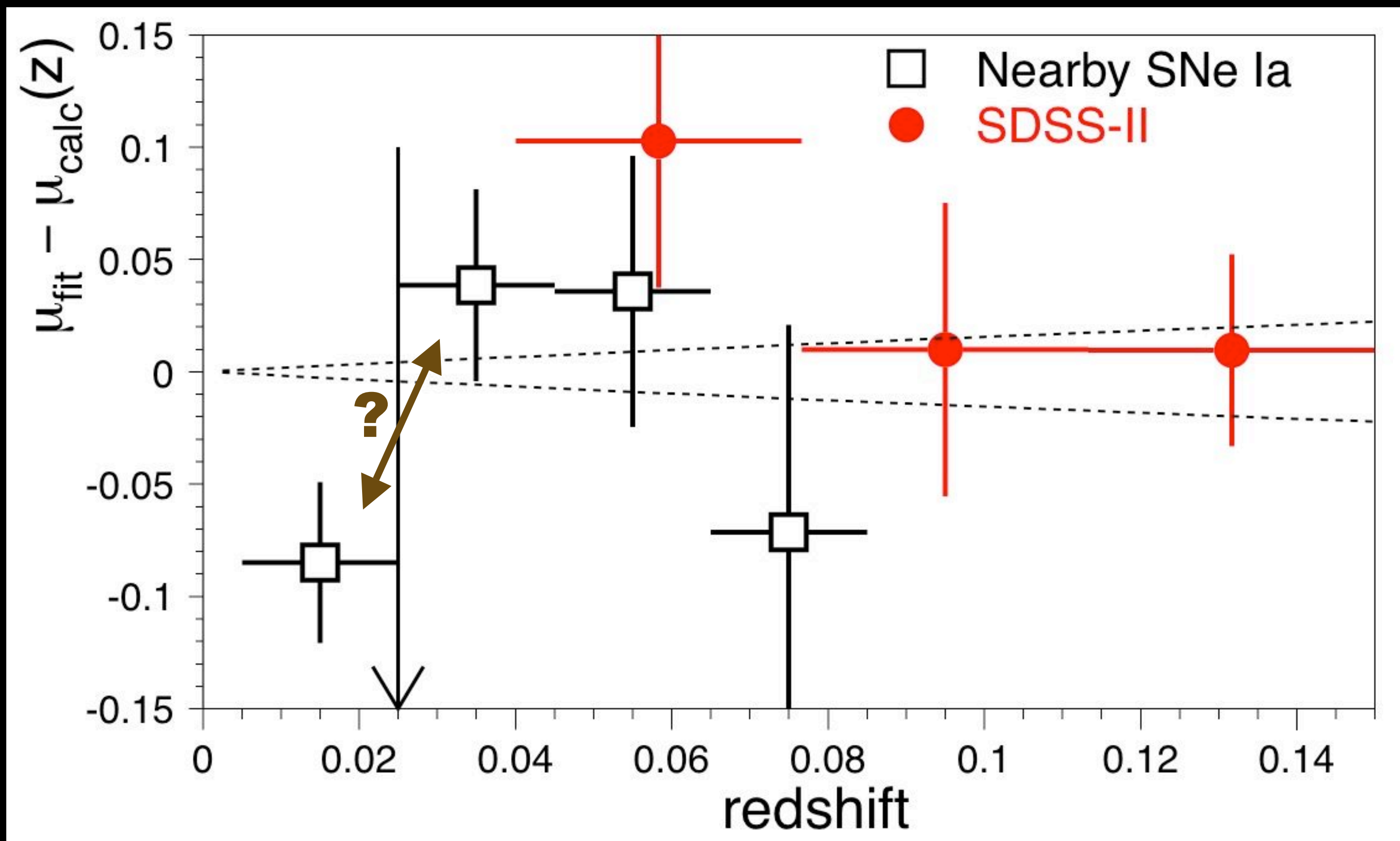
Total Error Contours
(stretch stat-contour along BAO+CMB axis



Hubble Anomaly

a.k.a "Hubble Bubble"

Conley et. al. astro-ph/0705.0367

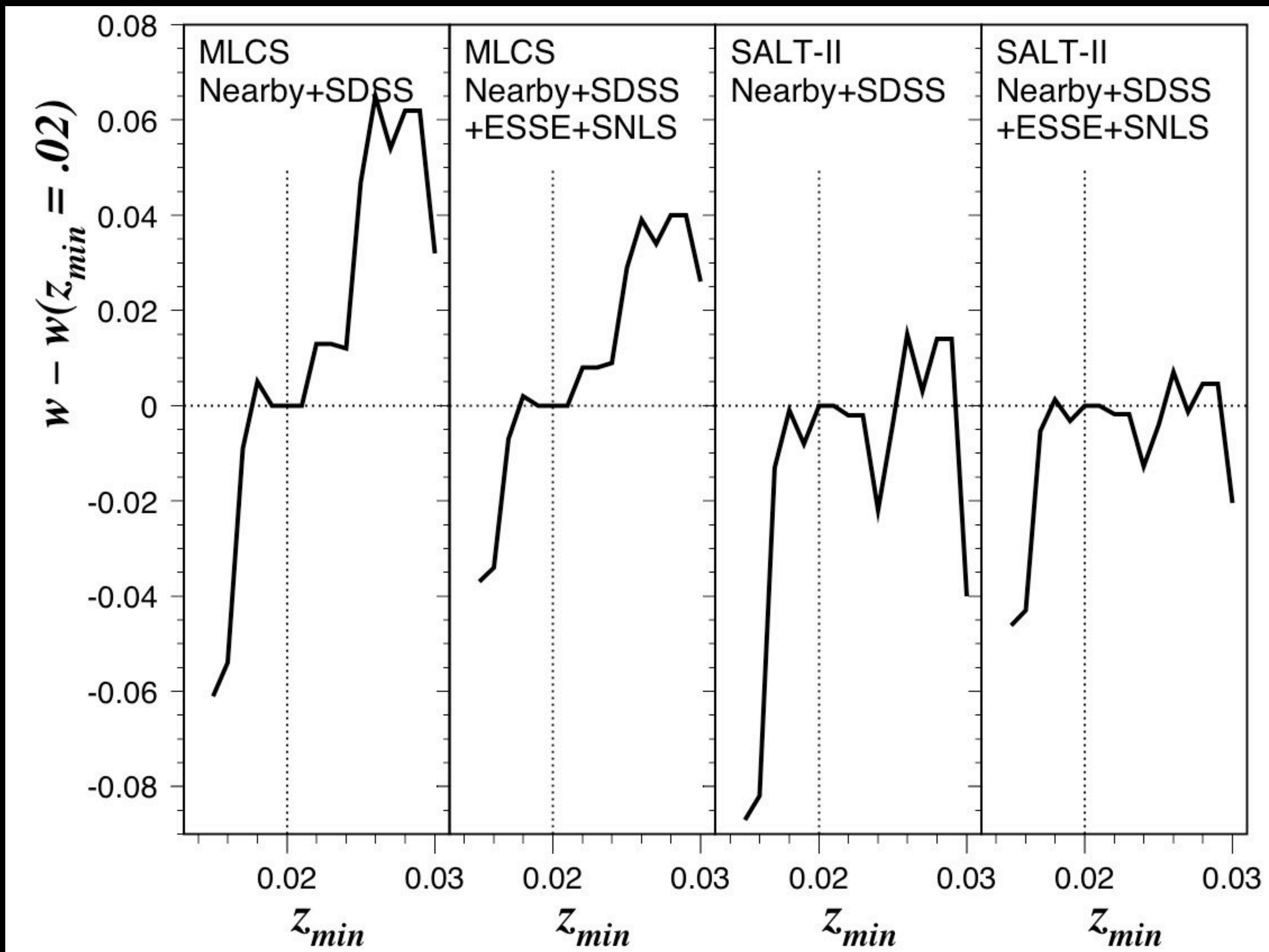


μ_{fit} from data; μ_{calc} calculated from concordance model

Hubble Anomaly

a.k.a “Hubble Bubble”

Conley et. al. astro-ph/0705.0367



Conclusions

- ☆ Paper in preparation (with 99 SDSS SNe Ia)
- ☆ side-by-side comparisons of MLCS vs. SALT2
- ☆ SDSS "*photometric* SNe Ia + z_{host}" are used to measure dust properties (RV) … important step toward using photo-SN in Hubble diagram, and quantifying survey efficiency.
- ☆ SDSS SN with $z < .15$ may help understand low-z Hubble anomaly.
- ☆ Need publicly available training codes to optimize training and evaluate systematic errors.
- ☆ all SDSS-based analysis (fitter & sim) is publicly available now … data available with paper.
- ☆ Three-season SDSS SN survey is done. Still acquiring host-galaxy redshifts to improve measurement of dust properties and for more SN Ia on the Hubble diagram.